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Fluvial Terraces and Post-Glacial River Incision Along the Farmington and Housatonic Rivers in Southern New England

Amberlee Nicoulin

B.S., Eastern Connecticut State University, 2011

A Thesis

Submitted in Partial Fulfillment of the

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At the

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Master of Science Thesis

Fluvial Terraces and Post-Glacial River Incision Along the Farmington and Housatonic Rivers in Southern New England

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2014

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ABSTRACT

River terraces are landforms that result from hydraulic responses associated with Quaternary climate and base-level changes, as well as tectonic and geomorphic processes. They can be used to interpret paleo–river levels along longitudinal profiles and assist in revealing the processes of river incision and knickpoint migration. This study uses fill and cut-fill river terraces as markers of river incision to address lithology controls on the transient response of watersheds to baselevel and climatic changes along the Farmington and Housatonic Rivers in Massachusetts and Connecticut.

This study utilized Geographic Information System (GIS) to extract longitudinal river profiles and compile datasets for stream terrace elevations. Fieldwork at select sites assisted in understanding the stratigraphy of terrace deposits. Conservative estimates are used to establish paleo-river levels (initial location of the river immediately post-glaciation) and study the spatial distribution of stream terraces for multiple reaches along these rivers in relation to observed bedrock knickpoints. From this, three different knickpoint migration and/or emergence scenarios were constructed through the use of these longitudinal profiles, terrace heights, knickpoints locations and known glacial history. These conceptual models assist in explaining complex slope and incision patterns observed along these rivers.

Results from this study show that the Farmington and Housatonic Rivers are in transient adjustment influenced primarily by bedrock legacy rather than base level controls since over the past 18 ka. Their highest, former river levels are aggradation surfaces of glaciofluvial, braided floodplains. Not only can we now better understand the previous shape and elevation of these rivers, but also the significance in bedrock legacy to patterns of incision. This research is fundamental to understanding post-glacial landscape evolution in southern New England, and the

methods used here can be easily transferred for use in other deglaciated regions around the world.

INTRODUCTION

In 1902, American geographer William Morris Davis published *River Terraces in New England* and an article in the American Journal of Science entitled, *The Terraces of Westfield River, Massachusetts.* Since that time, river incision and stream terraces have remained thought-provoking aspects of geomorphological research throughout Southern New England. This region is very complex due to its deglaciation history, which includes glacio-isostatic rebound, baselevel change, underlying bedrock, and fluctuations in climate. All of these variables make it difficult to interpret patterns of incision, as they too are not well understood. Here, we seek to understand how the use of Geographic Information System (GIS) analysis and modeling, when combined with fieldwork, can improve our understanding of the complex rivers dissecting the New England landscape (Figure 1).

This thesis uses river terraces as markers of river incision to address the following question: how does lithology control the transient response of watersheds to base level changes and changing climate? Baselevel controls, both regional and local, have a significant impact on the rate and style of incision by affecting stream gradients. Climate controls the amount of water and sediment a river may carry, and hence directly impacts incision. The role of underlying bedrock (i.e. rock strength) on landscape change is crucial, as knickpoints and locally high river gradients can also regulate incision. Terraces and river incision in southern New England reflect the general shift in climate and sediment fluxes associated with deglaciation and the specific role of bedrock knickpoints and differing baselevel controls during incision. By understanding the pattern of terraces and incision for both the Housatonic and Farmington Rivers, two rivers affected similarly by changing climate (glacial-interglacial cycles), but displaying differing roles of bedrock knickpoints and local baselevel controls, this thesis presents a detailed analysis concerning the spatial distribution of incision and how rivers respond and evolve given these controls. We use conservative estimates to establish paleo-river levels and subsequently analyze the distribution of stream terraces for multiple reaches along these rivers. Subsequently, we have constructed 3 new conceptual knickpoint migration models that help interpret incision patterns in the relation to the emergence of bedrock knickpoints during incision into glacial fill. Not only can we now better understand the shape and elevation of these rivers, but also the significance in bedrock legacy to patterns of incision.

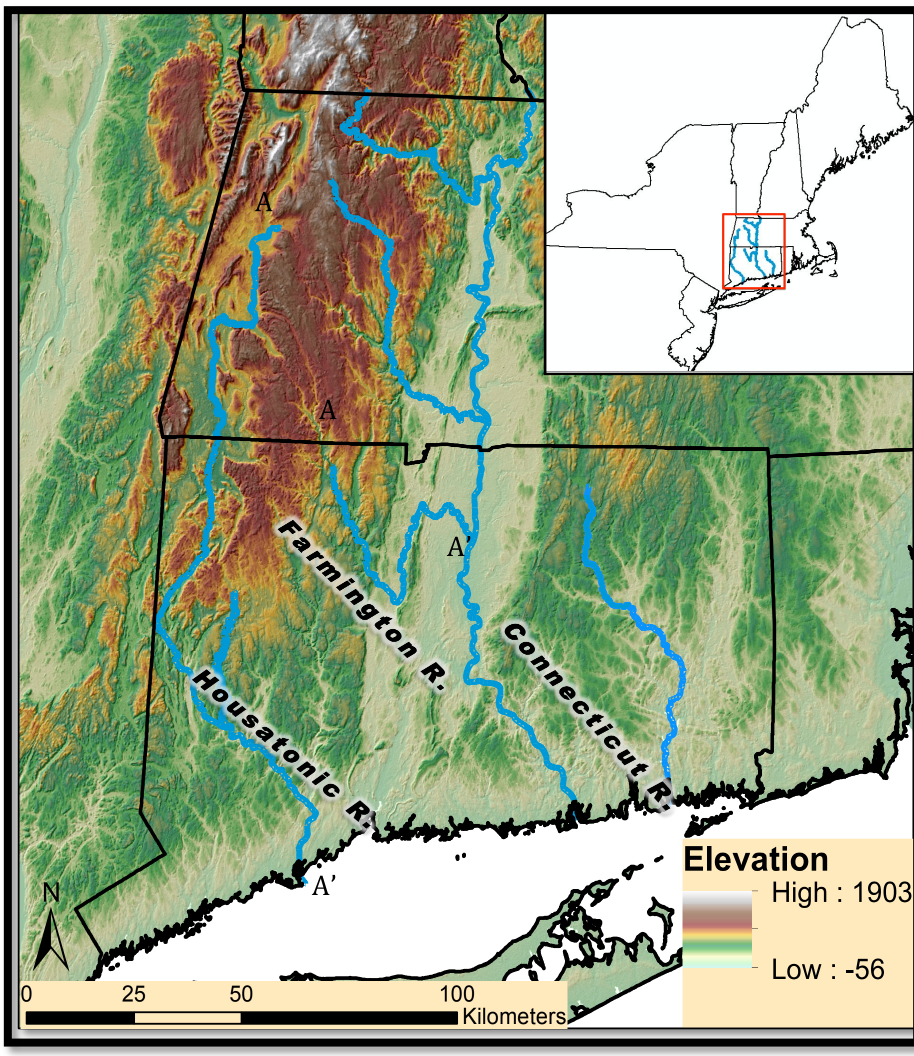


Figure 1. Location Map of the study site encompassing both the Housatonic and Farmington Rivers located in Massachusetts and Connecticut.

Background

River terraces are nearly ubiquitous features of river valleys and indicators of river incision (Zaprowski, 2005; Finnegan, 2012). They incorporate hydraulic responses associated with climate change, base-level fluctuations, and tectonic processes (Adams, 1945; Bull, 1990; Verhaar, 2008). Terraces are former floodplains, as terraces are not inundated frequently, if ever, during floods. Terraces are fixed geomorphic indicators in the river valley (Pazzaglia, 2012). These indicators can be used to interpret paleo–river levels along longitudinal profiles, calculate incision rates, and assist in understanding the processes of knickpoint migration (Dillon and Oldale, 1978; Blum and Törnqvist, 2000; Zaprowski, 2005; Gibbard and Lewin, 2009; Finnegan and Dietrich, 2011; Olszak, 2011; Finnegan, 2012; Macklin et al., 2013). Since river terraces were at one time a working part of the active river channel, they can be utilized to understand the timing and any external causes of abandonment (Bull, 1991; Merritts et al., 1994). Even though river channels only cover a small percentage of the land's surface, the surrounding area remains the location where the majority of denudation occurs due to sediment transport through the channel and the establishment of boundary conditions for hillslope processes (Schumm, 1979; Gilbert, 1980; Whipple, 2004).

Conditions for Terrace Development

Terraces form in response to changes in a fluvial system. River channel slope reaches equilibrium by transporting sediment and eroding into bedrock. When a threshold is reached, rivers can adjust to the new conditions and regain equilibrium by raising (aggradation) or lowering (degradation) the channel bed through sediment entrainment or incising bedrock (Davis,1902; Gibbard and Lewin, 2002; Bridgland, and Westaway, 2007). When there is a change in a river valley, it causes an adjustment in the river followed by incision or aggradation and typically the establishment of a new, lower or higher floodplain. Thresholds include a change in stream power (incorporating slope and discharge) or sediment supply. However, the precise response depends on the watershed substrate as well as climatic, tectonic, and base level settings (Pazzaglia, 2012). Terraces form at a variety of spatial and temporal scales, with both intrinsic and extrinsic controls. These controls include a change in river flow and sediment-discharge ratios, eustasy, climate change, tectonics, and isostatic adjustment (Maddy, 1997).

Terrace Varieties

Recognizing and understanding the variety of stream terraces is crucial to comprehending a river's history. Terraces are classified by their development, i.e. how they were abandoned by the river due to incision, meandering, etc. Three types of terraces are recognized through differences in aggradation, degradation, and substrate type (Figure 2). The first type is a fill terrace, which reflect deposition followed by erosion, and based upon a major event (e.g., deglaciation). After a valley is filled with sediment during aggradation, it will then incise into the sediment leaving behind fill and cut-fill terraces. Studying this variety of terrace allows us to determine the highest level of aggradation, time of deposition and time of abandonment. Cut-fill and strath terraces are both erosional and develop during lateral incision of the river channel. The primary difference between cut-fill and strath terraces is that a cut-fill terrace consists of alluvium or other unconsolidated material (i.e., incision into a previous high, fill terrace level), while strath terraces are formed during bedrock erosion. All three terrace types can have a thin veneer of gravel reflecting the actively transported sediment at the time of abandonment or may lack such a feature. In New England, if present, these deposits may cover irregular bedrock or unconsolidated glacial material or various origins, as the river has not had a chance to incise into that portion of the valley (Bull, 1990).

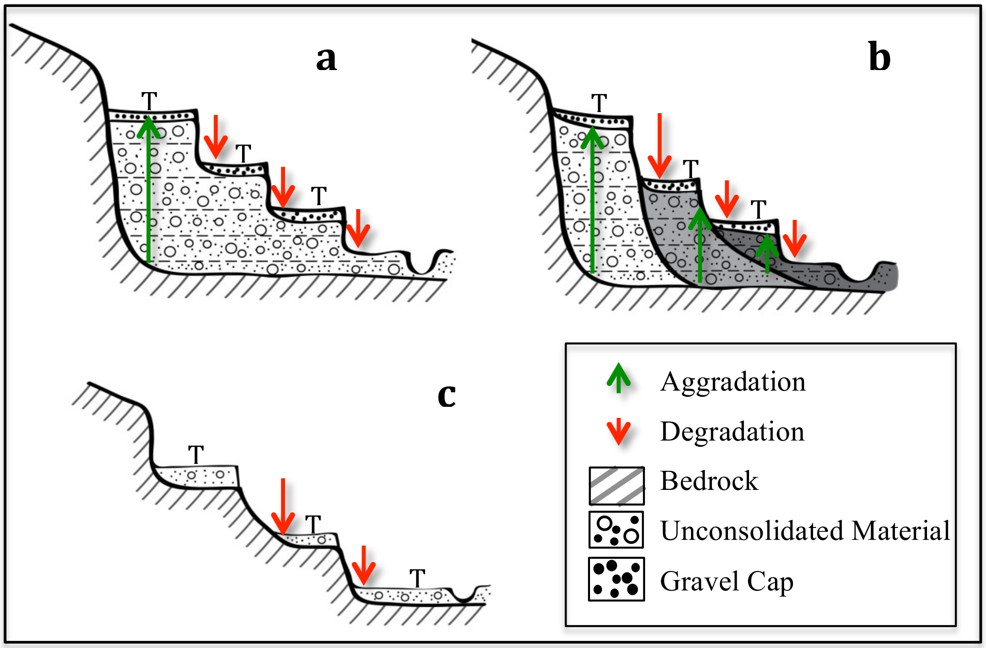


Figure 2. Three varieties of terrace formation derived from; a) fill terrace, b) cut-fill terrace, and c) strath terrace (Burbank and Anderson, 2007; Lewin and Gibbard, 2010; Merritts et al, 2011).

All three varieties of fluvial terraces can form in either paired or unpaired sets (Figure 3). Paired terraces are of equal height above the river on both sides of the valley. These paired sets are typically created during episodic events (e.g. large floods) that cause denudation, and may reflect the peak aggradation during deglaciation. However due to lateral erosion during such events, portions of paired terraces are typically destroyed, leaving small remnants behind and making them not as common to find as unpaired terraces. This is because paired terraces represent valley-wide thresholds, whereas unpaired terraces represent transient stages in local erosion. Even though paired terraces can be harder to locate, they are dominant in many valleys, making unpaired harder to find (Jahns, 1967; Stone, 2008). Paired terraces can be crucial to reconstructing paleo-river levels and past river gradients and are the only way of reconstructing valley-wide events. Unpaired sets do not have correlation from one side of the stream to the other due to continuous, concurrent vertical incision and lateral migration. Unpaired terraces are difficult to use when determining past river gradients, however they are still useful in understanding the river's incision processes (Bull, 1990; Merritts, et al., 1994; Bridgland, 2000; Gibbard and Lewin, 2009).

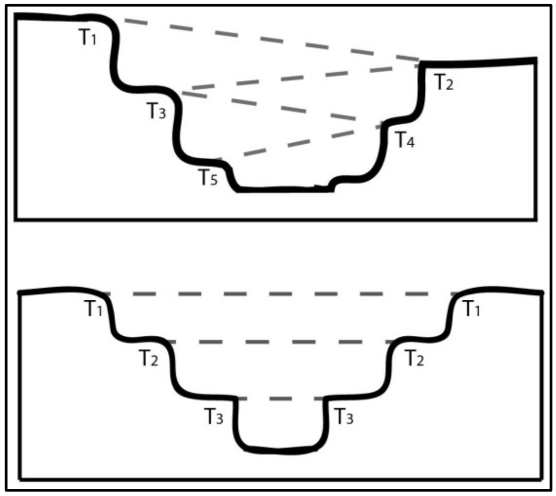


Figure 3. Comparison of a) unpaired terraces due to discontinuous incision, and b) paired terraces formed during continuous incision.

River Incision & Knickpoint Migration

Since river terraces are markers of incision, it is important to understand controls of river incision. Incision occurs when there are changes in sediment supply (Q_s), water discharge (Q_w), or base level rise/fall (slope) that cause changes in the average shear stresses exerted by active rivers on channel bottoms. Many models have examined river incision behavior and the development of longitudinal river profiles (Howard 1980; Whipple and Tucker 2002). Two prominent models of river incision considered here are: (1) transport-limited incision, where the divergence of the sediment transport sets the rate of incision (Howard 1980; Howard and Kerby, 1983), and (2) detachment-limited incision, where bedrock incision (rock strength, weathering, plucking, abrasion, etc.) and a stream's ability to erode the bed sets the rate of incision (Baker, 1974; Hancock et al., 1998; Whipple et al., 2000). Some studies suggest that a stream can incise into bedrock and still be considered transport-limited rather that detachment-limited, as long as it is sediment transport and not bedrock strength that sets the rate on incision (Howard 1980; Howard and Kerby, 1983). For mixed bedrock-alluvial bed morphologies, sediment flux is evidently important in the dominant processes of river incision into rock. The dynamics of bedrock channel behavior is most likely a combination of both transport-limited and detachment-limited settings. This is mainly evident within incision models that contain a strong dependence on sediment load (Whipple, 2004). The generalized stream power incision model has been widely used for predicting the rate of fluvial incision, particularly into bedrock. The model is expressed as:

$$E = KA^m S^n,$$

where E is bedrock river incision, K is a dimensional resistance to erosion, A is drainage area, S is slope, and m and n are non-dimensional (positive constants reflecting basin hydrology, hydraulic geometry, and erosive processes) (Berlin and Anderson, 2007).

Knickpoints are generally defined as an abrupt change in channel slope, that can be so steep to cause waterfalls, or more subtle like broad convexities seen only through river profile analysis (Burbank and Anderson, 2002; Whipple, 2004). Another, more classic, definition is that a knickpoint describes a discrete, steep reach that creates a local convexity in the general concave up equilibrium channel profile (Crosby and Whipple, 2006). Knickpoints can originate on main channels as a result of base-level change (local or regional), differential tectonic uplift (e.g. isostatic adjustment) or differential incision (Frankel et al., 2007). Evolution of knickpoints is a function of the amount and rate of sediment erosion or deposition within a knickpoint reach (an area of the river affected by the knickpoint). Erosion or deposition within this reach primarily relies on changes in sediment-transport rate, which is commonly expressed as a function of bottom shear stress caused by fluid flow over the channel bottom (Gardner, 1983).

Understanding the patterns in which a knickpoint behaves is crucial to understanding landscape response to base level fall and the corresponding sediment fluxes. Bedrock knickpoints can be a significant factor for patterns of river incision, especially if they are combined with unconsolidated material. Styles and rates of knickpoint behavior have been investigated using multiple techniques such as field observations (i.e. Miller, 1991; Seidl et al., 1993; Hayakawa and Matasukura, 2003), physical modeling (Gardner, 1983), numerical modeling of knickpoint recession (van der Beek et al., 2001), and simple modeling using longitudinal profile dating (Begin, 1988). Although many of these studies model a parallel retreat of the knickpoint due to detachment-limited incision, Gardner (1983) discussed other patterns of incision. These include slowed propagation of the knickpoint from backwards rotation, and base-level perturbation that is accommodated near the knickpoint or diffuses upstream due to transport-limited incision (Bishop et al., 2005).

It has been suggested that channels erode into bedrock through three different mechanisms: 1) vertical wear of the channel bed due to stream power, 2) scouring by periodic debris flows, and 3) knickpoint propagation (Seidl and Dietrich, 1993). Local steepening associated with knickpoints concentrates erosive energy, which results in streambed erosion through abrasion, pothole formation, plucking and cavitation down stream (Frankel et al., 2007). Whipple (2004) suggests that the degree to which these physical and chemical weathering may favor particular erosional mechanisms is not well known, however substrate and environmental conditions play a large role. Many studies have discussed the mechanics and relative efficiency of various physical erosive properties, including critical thresholds such as floods such as those due to glacial outbursts or landslide-dam breaks (Baker, 1974; Hancock et al., 1998; Sklar and Dietrich, 1998; Whipple et al., 2000). Frankel et al. (2007) conducted flume experiments in the to understand the evolution of a knickpoint in a bedrock channel with vertical bedded substrate with alternating resistance. Their study exemplifies the complexity of knickpoint evolution, unsteadiness of bedrock channel erosion, and larger lag times in natural fluvial systems that are in the process of adjusting to a lowering of baselevel (Frankel et al. 2007). Another pertinent study came from Cantelli et al. (2004), in which physical models were ran of upstream-migrating erosion narrowing and widening caused by dam removal. They found that, post dam removal, rapid vertical incision decelerates to lateral erosion.

Knickpoints result from differential erosion that is due to changes in lithologic resistance (faulting or stratigraphy), and can result in patterns between knickpoints and terraces downstream (Seidl and Dietrich, 1992). Knickpoint evolution can occur in heterogeneous materials, however it is important to note that critical shear stress is needed to initiate motion of bed materials. Therefore, morphologic changes of a knickpoint reach are a function of the relationship between bottom shear stress (downstream momentum of flow) and critical shear stress (required to mobilize sediments) needed to create motion (Gardner, 1983). Many studies have demonstrated the mechanical properties of substrate (homogenous, stratified, cohesive, non cohesive, etc.) influence whether the knickpoint face (the portion of the knickpoint with the highest slope) progressively decreases gradient or whether the knickpoint migrates upstream with varying degrees of incision upstream of the lip (Crosby and Whipple, 2006). Figure 4 shows two well known knickpoint migration scenarios that show a) parallel retreat due to high stream power in a detachment-limited (sediment transport capacity exceeds sediment supply) river system, and b) depicts both vertical incision and migration upstream in a transport –limited (sediment flux dependent) river system that incises into unconsolidated fill that is easily transportable (Zaprowski, 2005; Gran et al., 2011).

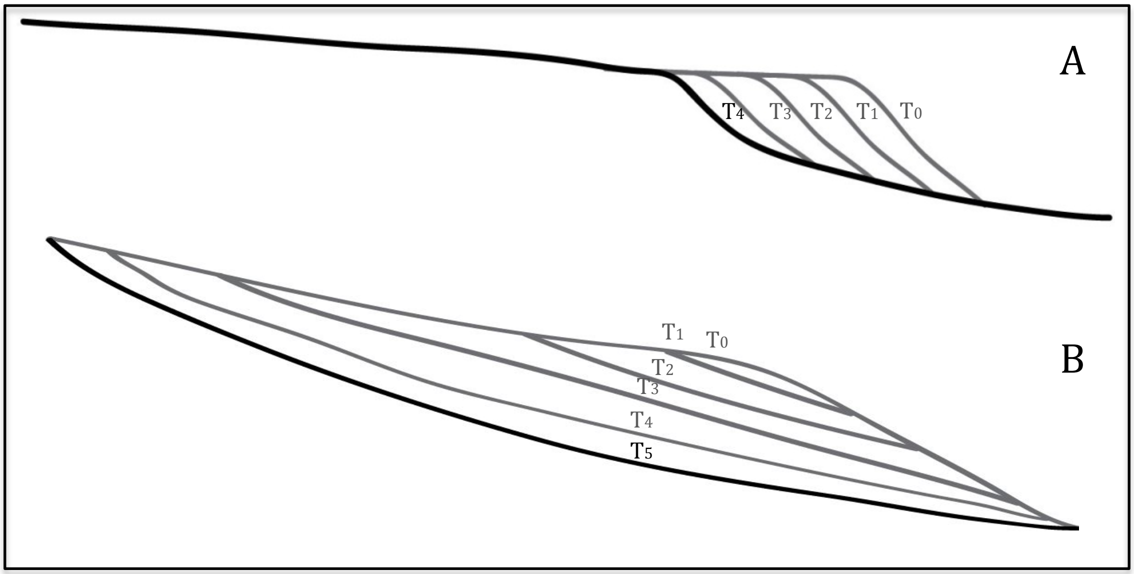


Figure 4. Knickpoint migration scenarios; 8a shows parallel retreat due to high stream power in a detachment limited river system, while 8b depicts both vertical incision and migration upstream in a transport –limited (sediment flux dependent) river system that incises into unconsolidated fill that is easily transportable (Zaprowski, 2005; Gran et al., 2011).

Climatic Influences on Incision

Climate is a natural forcing that can influence basin hydrology, sediment supply, topography, soil, vegetation, baselevel, and fluvial regimes (Florsheim et al., 2013). Climate directly influences global sea level and therefore sets the ultimate base level for all river systems. Climate change can also be considered to be a large factor for aggradation and degradation. When climate becomes a major influence, the profile will typically gain the characteristics of a graded, concave up shape that is locally controlled by discharge and sediment flux (Berlin and Anderson, 2007). Climate induced incision is a short-lived condition in the overall evolution of a stream's longitudinal profile, limiting the relief in a landscape.

Climate controls vegetation (variables such as subsoil and evapotranspiration), which controls flood response and sediment supply. For example, colder climates (e.g. immediately post-deglaciation) produce regions with little to no vegetation. This can lead to an increase in runoff and subsequently river incision, as there is a lack of a root system as well as covering from episodic events. Warm, dry climates can produce a similar effect, and often produce high-power flash floods when solitary precipitation events do occur. However, if the climate is warm and wet, there still can be significant river incision due to the excess of water discharge (Tucker and Slingerland, 1997; Tebbens et al., 2000; Moody and Meade, 2008; Bridgland et al., 2010).

Study Area

This study focuses on southern New England; a region can be subdivided into 4 major geologic provinces that have similar physiographic characteristics. These include the Western Highlands, the Connecticut Valley Lowland, the Eastern Highlands, and the Coastal Lowlands (Patton, 1988). This thesis covers the Western Highlands and the Connecticut River Valley in Connecticut. The Western Highlands has the greatest relief in the region (exceeding 300 m in some locations), and includes the Berkshire Hills and Taconic Mountains. Valleys incise into late Paleozoic and Proterozoic metamorphic and igneous bedrock along with Cambrian and Ordovician carbonate bedrock (i.e. marble). The Connecticut Valley Lowland is a Mesozoic half-graben trending north-south with a low relief underlain by sandstones, siltstones, and shales, as well as basalt-capped ridges forming a west-facing cuesta (Patton, 1988).

The field area for this research consists of the Connecticut and Housatonic Watersheds in western and central Connecticut (Figure 1). Within these watersheds, larger rivers were studied including the Housatonic River (Housatonic River watershed) in western Connecticut and Massachusetts, and the Farmington River (Connecticut River watershed) in west-central Connecticut and Massachusetts. The study area includes these two rivers, both with differing characteristics in basin area, relief and valley structure.

Quaternary History of Southern New England

Southern New England has undergone at least four glacial-interglacial (Milankovitch) cycles, each consisting of approximately 100,000 years with the last ending in the late Pleistocene. The Quaternary Period encompasses the past 2.6 million years and is broken down into the Pleistocene and Holocene epochs, with the Holocene consisting of only the last 11,700 years. This period, along with the recently recognized Anthropocene (18^{th} century to present) is not only our key to understanding the recent past, but also our near future, making it extremely significant to study for human impacts and future consequences. Changes in landscape during the Quaternary period have consisted of both: (1) alteration in climate and geomorphic processes and (2) human modification, prominently in the past 5,000 years (Delcourt and Delcourt, 1988), primarily in last 400 years.

The emergence and retreat of the heavy ice load over a large portion of North America has led to many sedimentation and landscape transformations throughout the Quaternary period. During the last glaciation, a sector of the Laurentide ice sheet spread across Vermont, New Hampshire, Massachusetts, and covered all of Connecticut moving from north-northwest to south-southeast, and reached its maximum extent on Long Island around 26.5 kya (Figure 5) (Sirkin, 1982; Stone et al., 2005, Clark et al., 2009). During the development of the Laurentide ice sheet, the lithosphere below was depressed causing what is known as an isostatic depression. This glacio-isostatic adjustment refers to the change in elevation of the lithosphere due to the loading and unloading of an ice sheet. Isostatic depression is the downward modification of the lithosphere under the weight of the ice sheet, while isostatic rebound refers to the upward motion of the Earth's surface after unloading of the ice sheet (Oakley, 2011). As the ice sheet retreated, it left behind thick glacial deposits overlying bedrock throughout the Connecticut Valley. The previously depressed terrain began to rebound upward after the ice sheet retreated north of central New England, producing a landscape that has undergone glacio-isostatic uplift of about 0.8 m/km to the north- northwest (Oakley, 2011). Uplift in the mountainous headwaters of New England occurred when the forbulge (a bulge on the lithosphere in front of the ice load) migrated northward and increased upstream relief while at the same time, subsidence is occurring downstream, lowering the baselevel (Florsheim et al., 2013). Since the retreat of the Laurentide Ice Sheet ~21-18 ka and subsequent uplift, the region has been shaped greatly by both fluvial and glaciofluvial processes.

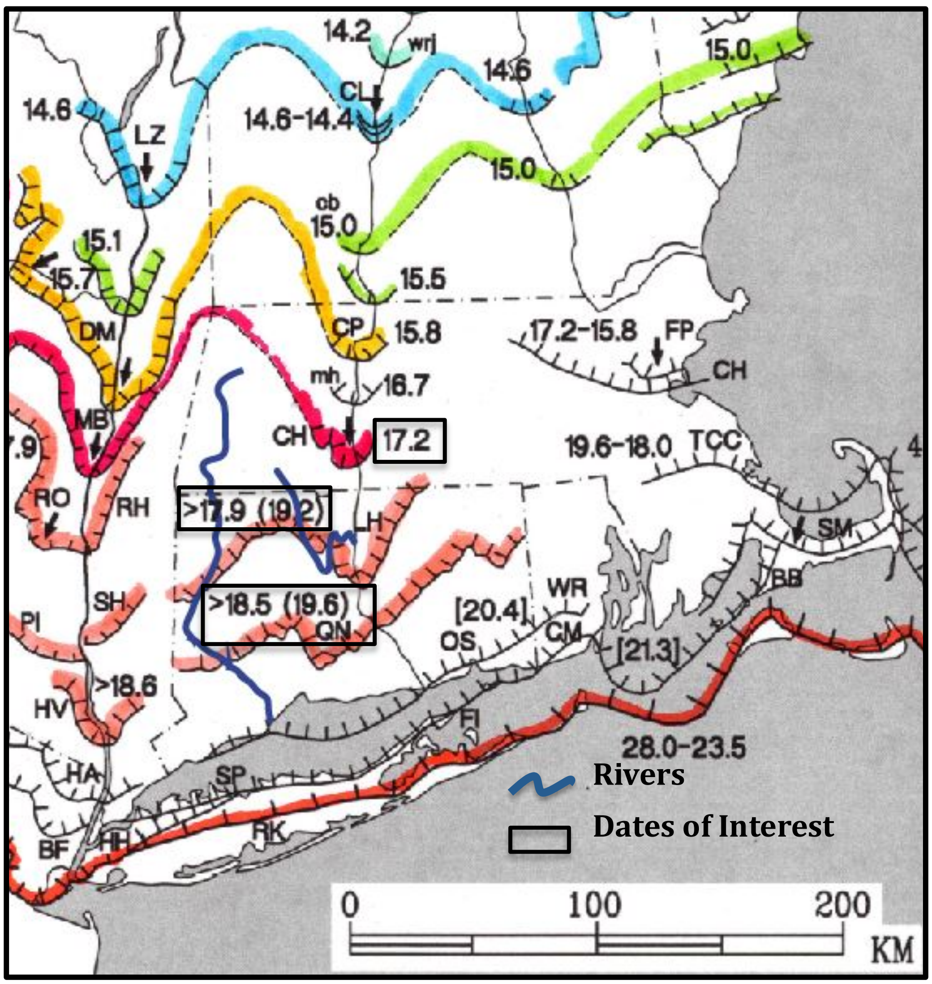


Figure 5. A New England map derived from the Tufts Varve Chronology Project depicting calibrated ages for ice retreat during the Wisconsinan deglaciation. The Housatonic and Farmington Rivers have been added to show the significance of ice retreat on the study site.

Glacial lakes were also prominent in the region due to numerous ice and sediment dams forming during retreat (Figure 6). Glacial Lake Connecticut occupied the majority of the region now known as the Long Island Sound (Stone et al., 2005). Moraine construction and deltaic deposition into Glacial Lake Connecticut completely filled the lower part of the valley, while successive glacial lakes were being dammed north of Glacial Lake Connecticut (i.e. each small lake was dammed by the one south of it).

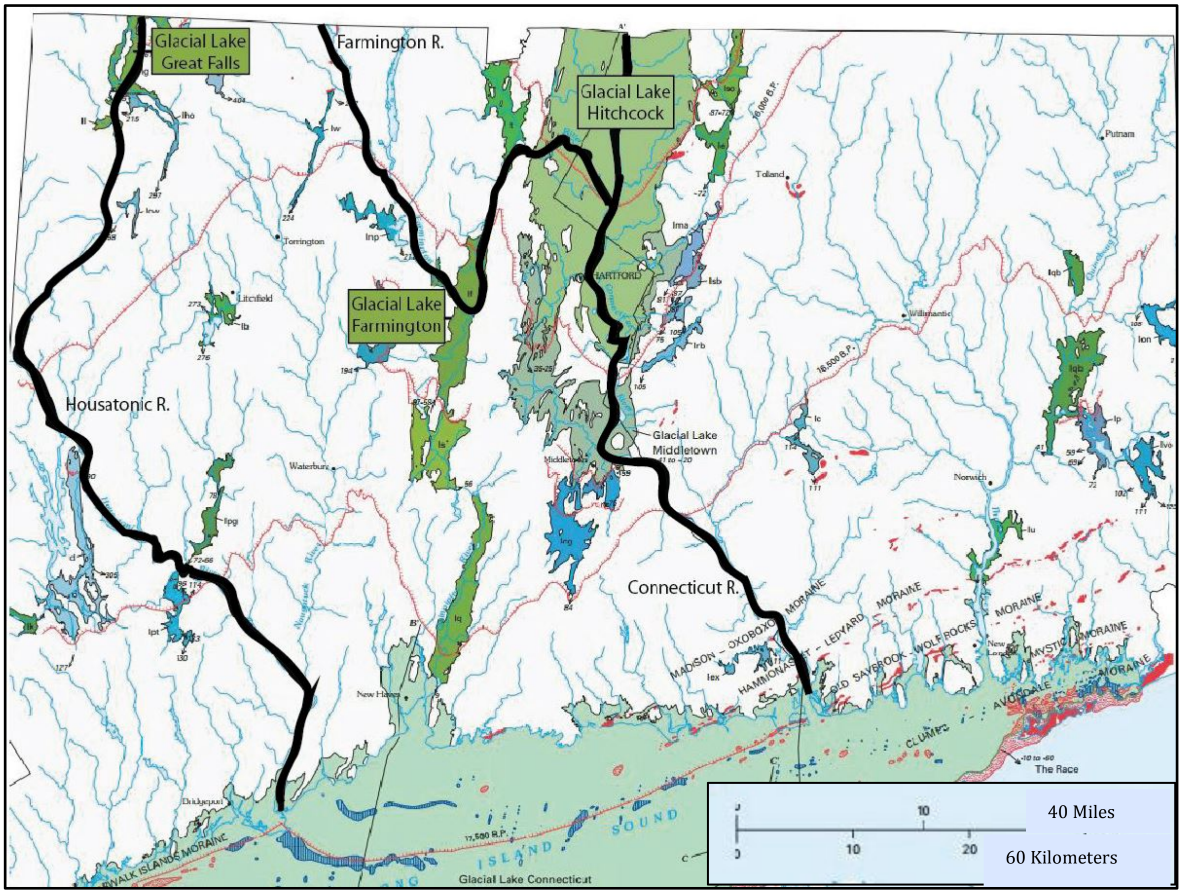


Figure 6. Glacial Lake locations across Connecticut immediately post deglaciation with rivers represented in black.

Deglaciation of Massachusetts and upper portions of Connecticut was dominated by sedimentation in Glacial Lakes Hitchcock and Middletown (Connecticut only). Glacial Lake Hitchcock existed in the upper Connecticut River basin in Connecticut, Massachusetts, Vermont, and New Hampshire with a total length of approximately 298 km. The Connecticut River valley was dammed at 46 to 49 m (present elevation) near Rocky Hill and Glastonbury by deposits of Glacial Lake Middletown. However, when the ice margin retreated into the Hartford Basin, the water from Glacial Lake Middletown covered the upcoming New Britain Spillway, and early ice-marginal deltas in the Hartford basin were controlled by Glacial Lake Middletown. It was not until Glacial Lake Middletown's elevation had dropped below 35 m above sea level that the New Britain spillway could emerge and Glacial Lake Hitchcock could become its own body of water. A portion of the New Britain spillway eroded into till and stratified drift so that water levels dropped from 35 m to 25 m in elevation. This is evident in deltas along the Connecticut River Valley that depict the gradual lowering (Stone et al., 2005). It was then that the "stable phase" of Glacial Lake Hitchcock began, around 15,000 years ago.

As isostatic rebound continued, the remains of glacial Lake Hitchcock in Connecticut and Massachusetts drained through the New Britain Spillway causing a "post-stable phase" of the lake. The rivers that flow into the Connecticut River began pro-grading newer deltas into the valley, causing the rivers to incise further down into glacial deposits, as well as the original deltas they had created during initial drainage before "post-stable phase" of the Glacial Lake Hitchcock. From this point, approximately 13,500 years ago, many rivers continued to incise, forming terrace levels and new floodplains, reaching their current locations that we see today (Figure 7).

Changes in both regional/ultimate and localized baselevel can have numerous impacts on the evolution of rivers. Regional baselevel is the eustatic sea level for the region, and is the result of tectonic upheaval or subsidence of the surface and eustatic rise or fall of sea level (Merritts et al., 1994). There have been numerous studies on regional base levels during the Quaternary period that aid in the research of river incision (Dillon and Oldale, 1978; Fairbanks, 1989; Litchfield and Berryman, 2005; Shulte et al., 2007; Verhaar et al., 2008). Dillon and Oldale (1978) conducted a study concerning the sea level curve for the mid and north Atlantic region using seismic-reflection profiles. Results from this study allowed for an update of the maximum sea-level elevations from what was previously believed (as high as 120m), is now thought to not exceed 100m. This newer idea on maximum baselevel is derived from the integration of tectonic (i.e. glacio-isostatic) effects on these sea-level curves.

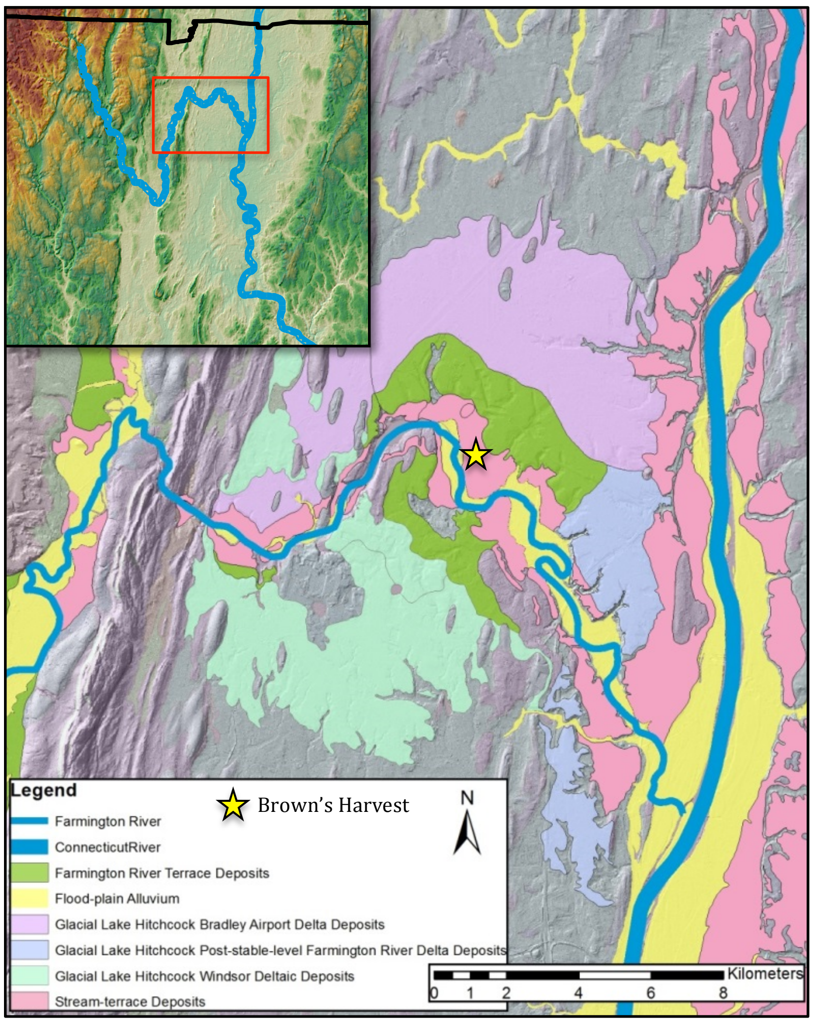


Figure 7. A surficial map showing Quaternary deposits mapped by Stone et al., 2005 for a downstream portion of the Farmington River.

Housatonic River Watershed

The Housatonic River Watershed covers 5045 km^2 in western Connecticut and Massachusetts (Figure 1). Major tributaries within this watershed include the Tenmile River in New York, the Williams, Green and Konkapot Rivers in Massachusetts, and the Shepaug, Pomperaug, Naugatuck and Still Rivers in Connecticut. The Housatonic River makes up the majority of the watershed, and stems from 4 different sources in western Massachusetts before flowing 240 km southwest until reaching Bull's Bridge in Connecticut where it cuts south-southeast into the Long Island Sound at Milford Point. The river has a relief of 435 m with the upper portion of the river being more constricted by bedrock and the lower portion alternating between a constricted and broader mixed bedrock and alluvial valley. Within the valley, bedrock types include gneiss, schist and marble, while Quaternary deposits range from terraces, Housatonic River deposits, glacial meltwater deposits, glacial lake deposits, and both thick and thin till. The river flows over many bedrock knickpoints, some now built up with dams, leading to great discontinuity of stream power, relief and complexity throughout the river system. Stone et al. (2005) mapped stream terrace deposits sporadically adjacent to the rivers in Connecticut (Massachusetts is still in the process of being mapped), typically in reaches that contain more unconsolidated materials than bedrock.

Connecticut River Watershed

The Connecticut River Watershed covers 28,500 km^2 in New England and a small portion of Canada. The Connecticut River begins in Chartierville, Quebec and flows into the Long Island Sound at Old Lyme, Connecticut with a distance of 660 km. The study area of interest for this project is only covered in Massachusetts and Connecticut (Figure 1). In this area, the Connecticut has a relief of 814 m, which is low gradient for a river of this proportion, and flows south within its broad valley through major cities such as Springfield, Massachusetts and Hartford, Connecticut. There are over a thousand dams located along this watershed's tributaries and a dozen on the mainstream. Specifically, the Farmington River, which is of interest to this study, is 129.4 km long (from it's west branch) with a relief of 361 m as it flows from southwest Massachusetts into central Connecticut where the river joins into the Connecticut River. The Farmington River is the Connecticut River's largest tributary, just barely larger than the Westfield River immediately to the north. The Farmington contains both mill and hydroelectric dams throughout its channel on relatively small knickpoints. A unique element to this river is that it flows in many directions, beginning southeast in Massachusetts into Connecticut, cutting quickly northeast through Glacial Lake Farmington Deposits, and finally flowing east into the valley and Connecticut River. However, the Farmington may have flowed south-southeast entirely instead of cutting northward before the last glaciation. Evidence supports that glacial lakes as well as sediment and ice dams caused the river to change its course post-deglaciation (Stone et al. 2005). Morphologic and stratigraphic evidence confirms that Glacial Lake Hitchcock was located at the outflow of the river until approximately 13,500 kya. While less in known about Glacial Lake Farmington, a smaller lake with fluviodeltatic deposits that suggest it reached a peak elevation of 93 meters. The spillway for this lake was originally across glacial till at approximately 67-58 meters in elevation, however after buried ice within the Quinnipiac Valley melted which caused lowering of Glacial Lake Southington (due south), it allowed Glacial Lake Farmington to change its spillway into lake Southington deposits around 16.2 kya. The river cuts over exposed bedrock approximately 25km upstream to the mouth as the water flows over the Holyoke basalt traprock ridge before winding through more unconsolidated materials including till and deltaic deposits. Stream terrace, Farmington terrace, and upper

Farmington deposits are abundant along the river, except for the portion of river that flows in a northward direction. Glacial tills and floodplain deposits are also ubiquitous throughout the Farmington River watershed.

Local Studies on Terraces

Detailed river incision processes have been investigated in other deglaciated regions of the United States such as in Washington State (Wegmann and Pazzaglia, 2002), and in the Minnesota River Valley (Gran, 2011; Gran et al., 2013), but have yet to be examined extensively in southern New England. Explanations of terrace development in this region have been previously attempted with restricted data and understanding of New England's Quaternary history (Davis, 1902; Jahns and Willard, 1942; Merritts et al., 1994; Stone, 2008). The limited knowledge of these features in the area leaves questions as to the effects of climate change, isostatic rebound, knickpoint migration and base level controls since the Last Glacial Maximum.

There have been a few field studies on river terraces in New England over the years, going back as far as 1902, when William Morris Davis, began his work on terraces adjacent to the Westfield River in Massachusetts. Davis sought to understand the pattern of terraces in New England, which showed the narrowing width of the river's fluvial plains during terrace formation from highest to lowest terraces. He explained this narrowing and terrace formation with three hypotheses; 1) a decrease in river volume (discharge) following isostatic rebound, 2) an alternating cycle of uplift and down-cutting of the river during shorter and shorter intervals, and 3) a slow regional uplift and local effect on the control of lateral river erosion by exposed bedrock ledges at the base of terrace scarps, preserving terrace plains above outcrops (Davis, 1902; Stone, 2008).

Later on, Stone (2008) revisited Davis' work to create a modern interpretation, examining the physical characteristics and distribution of bedrock, glacial, and post-glacial deposits in the Westfield River lower-basin reach. Stone (2008) discusses chronologically organizing the high, intermediate and low terrace levels, giving calibrated carbon-14 dates to each set ranging from 17 to 9 kya. This is one of the only detailed studies in the area that discusses dating terrace flights (based on a regional chronology) to interpret post-glacial river incision (Figure 8).

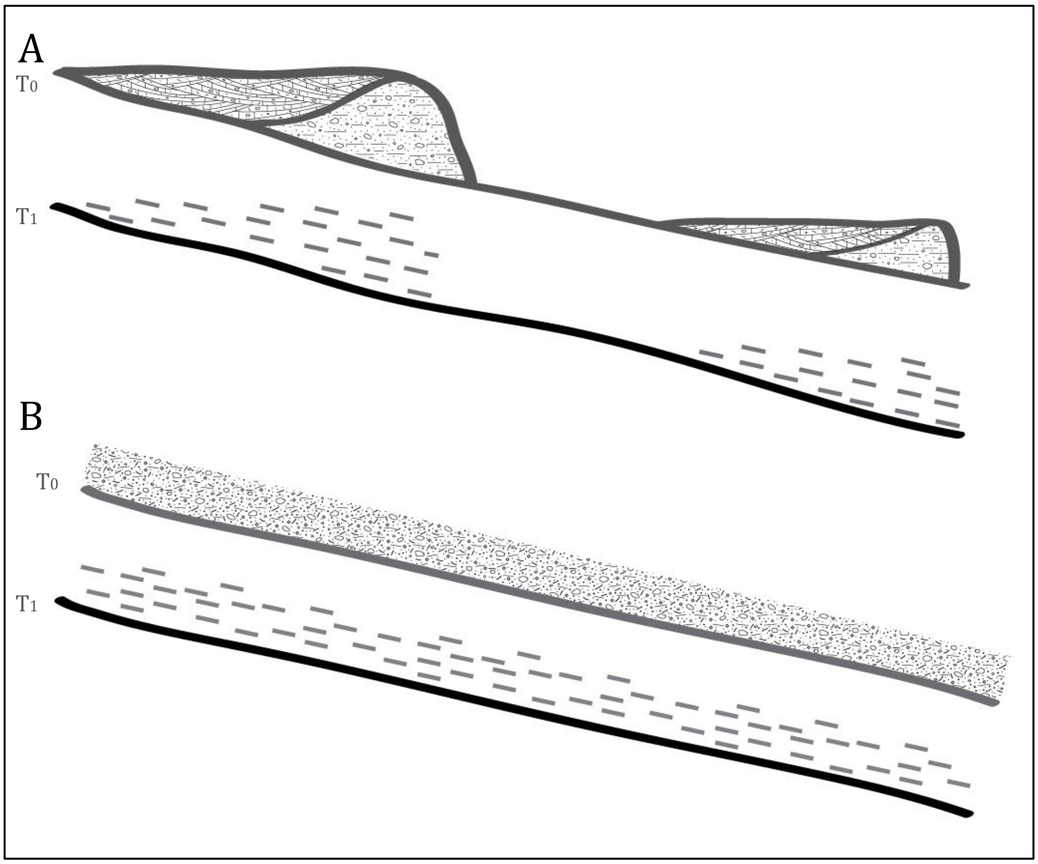


Figure 8: Examples of longitudinal filling patterns for southern New England rivers; 8a shows incision into sediment dams and 8b depicts widespread incision into glacial fill.

Another earlier study by Joseph Barrell (1920) later discussed by George Adams (1945), on upland terraces throughout southern New England focused on understanding how marine terraces form and show incision history. A more recent study was conducted by Tim Whalen, a graduate student from the University of Vermont, who focused on field-mapping terraces along the Huntington, Little, and Mad Rivers in the Winooski drainage basin in Vermont. His time went primarily to surveying cross-sectional profiles of the river valleys to map terraces heights, as well as trenching multiple terrace deposits for sediment analysis and carbon-14 dating (Whalen, 1998). Whalen discusses the difficulty of understanding terraces and alluvial fans in deglaciated regions due to the complications of glacio-isostatic adjustment. After utilizing knowledge of New England's climate history, along with previous and newly collected carbon-14 dates, Whalen makes a point in his thesis that further studies need to be conducted, and additional dates need be determined to further our understanding of terrace development in a deglaciated landscape such as New England.

METHODS

This study is focused on the Farmington and Housatonic Rivers in Connecticut and Massachusetts. Preliminary analysis of additional rivers in southern New England (Deerfield and Westfield Rivers in Massachusetts, Willimantic River and Thames River in Connecticut, Connecticut River in Massachusetts and Connecticut) is included in Appendix VI but will not be presented or discussed. These methods pertain to the process of extracting longitudinal river profiles and mapping terrace heights along the profiles as applied in all rivers studied.

Fieldwork

Fieldwork consisted of visiting the Farmington and Housatonic Rivers as well as isolated locations throughout Connecticut where stream deposits mapped by Stone et al. (2005) could be studied. Locations for field work were selected by isolating mapped terraces by Stone et al. (2005) adjacent to the Housatonic and Farmington Rivers, identifying potentially exposed terrace faces as areas of high slope in the slope maps, and prioritizing size of the deposits, the possibility of multiple terrace levels in one location, and accessibility to the field site. Many field sites were only given a preliminary analysis, which included surveying of previously mapped fluvial and glaciofluvial deposits, recording GPS points, photographs, and digging test pits (.5-1m deep). A few locations were chosen to trench pits 3-5m in depth to analyze the substrate as well as look for wood fragments for carbon-14 dating. Unfortunately, there were no items found that could be utilized for dating due to a lack of vegetation post-deglaciation. After pits are dug, exposed sediment was photographed and sediment samples were collected at depths where there was a change in substrate.

Geographic Information System (GIS) Analysis

Terrace analysis consisted of combining previously mapped stream terraces and fluvial deposits throughout Connecticut (Stone et al., 2005) with Digital Elevation Models (DEM) to extract and map terrace heights along longitudinal profiles of the rivers studied. All analyses was carried out in ArcGIS. The Quaternary deposits mapping of Stone et al. (2005) (1:24,000) is available in digital format for direct use in ArcGIS. Deposits that were analyzed included all deposits associated within fluvial process preserved within the valley of rivers studied, including map units floodplains, stream terraces, Farmington terrace deposits, Upper Farmington River deposits, Upper and Lower Housatonic River deposits, meltwater deposits (from proximal and distal meltwater streams), and various glacial lake deposits (i.e. Glacial Lake Hitchcock, Glacial Lake Farmington, and Glacial Lake Great Falls). DEM sources and resolutions varied along the study rivers. For portions of the Housatonic and Farmington Rivers that lie in Massachusetts, a 10m DEM data from the National Elevation Dataset was used. In Connecticut, two higher resolution DEM datasets were available: (1) a 2000 statewide LiDAR (Light Detection and Radar) dataset distributed by the Center for Land Use Education and Research (CLEAR) and available as a 10ft resolution DEM; and (2) a 2011 LiDAR dataset for northwest Connecticut distributed by the Natural Resources Conservation Service (NRCS) and available as a 1m resolution DEM. Slope maps and hillshade images from each DEM type were derived and used to visually study the river valleys of interest.

Longitudinal profiles of the Housatonic and Farmington Rivers were created by hand, digitizing the centerline of the streams (measuring the top of the water level) in ArcGIS and extracted elevations from DEMs. No consideration was taken for centering digitized rivers on modern thalwegs due to DEM resolution and incomplete information on thalweg location. Since the rivers covered many DEMs, the profiles were exported to Microsoft Excel and converted to meters as necessary. The profiles were then exported to Mathwork MATLAB, where a smoothing parameter was used to eliminate outlying spikes in the data. Spikes are typically due to bridges or dams across the river, as well as anomalies in the DEM data. As expected, more spikes occurred in lower resolution DEMs. After smoothing, the plots were exported back to Excel for profile analysis (e.g. noting changes in channel steepness location of man-made dams, and any other significant features along the river).

Digitized rivers were labeled at every kilometer so as to serve as the basis for referencing topographic cross sections and terrace heights analyzed in ArcGIS to longitudinal profiles in Excel. Always starting river right to river left (the sides of the rivers when facing downstream), 110 cross sections for the Housatonic River and 160 cross-sections for the Farmington were extracted and used to identify terrace and other deposit heights (Figure 9). To assign heights to deposits an average elevation and height (calculated as the difference between the deposit and river elevation in each cross section) was extracted. This is necessary as many deposits, specifically river terraces, are not completely flat in profile (Figure 9). The middle of the deposit was typically chosen, as slumping or erosion can very well affect either end of the deposit.

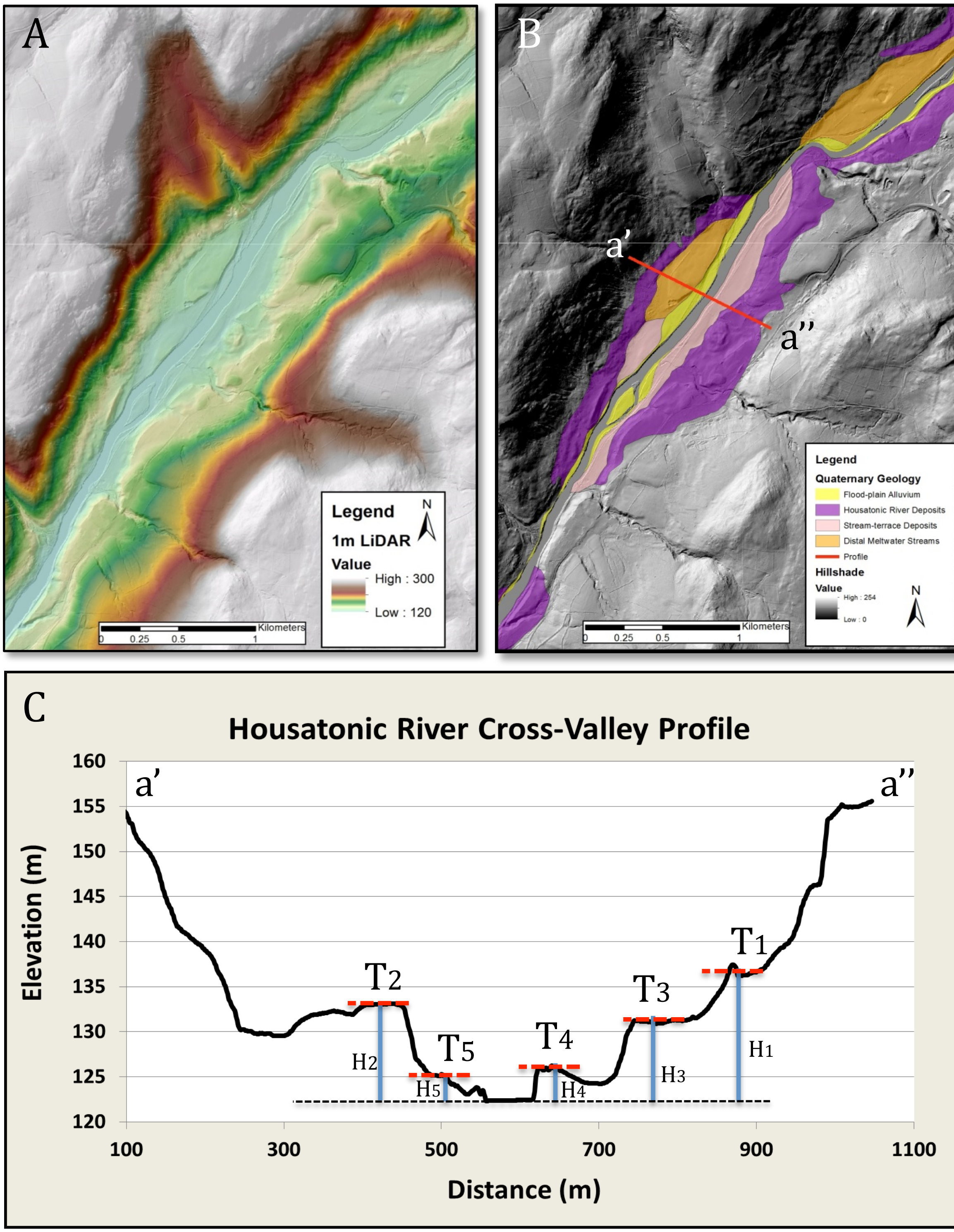


Figure 9. An example of a portion of the Housatonic River in Connecticut and the steps showing the process of collecting terrace heights by use cross-valley profiles in GIS with bot DEMs and the Quaternary deposit map by Stone et al. (2005). Figure 9a shows how a DEM shows the multiple levels of elevation change for the reach of the river; 9b shows a hillshade with the Quaternary deposits overlain, and the location of the cross-section extracted in red. 9c is the extracted profile with the terrace height locations highlighted.

Locations of the cross-sections were based upon ideal sites to retrieve deposit heights where clearly mapped terraces of the Stone et al. (2005) and other deposits of significance were found. Treads of terraces and correlating incised deposits are not extracted due to a lack of high-resolution data in some locations (i.e. Massachusetts) and anthropogenic impacts on those with higher resolution.

To address issues associated with multiple DEM sources and resolutions, an error analysis was completed in 15 stream terrace locations along the Housatonic River where 10m NED, 10ft LiDAR, and 1m LiDAR were all available in one region (northwest Connecticut) (Figure 10 and Table 1). For each of the 15 locations, the elevations of one major terrace and the stream bottom were recorded using each of the three DEM types. Stream elevations were subtracted from the terrace elevations to obtain a height of the terraces. Then, the 10ft and 10m DEMs were divided by the 1m DEM to get a ratio, assuming the 1m LiDAR is the most accurate due to its higher resolution. Standard deviations were then calculated to then get a +/- error analysis.

Table 1. Terrace Elevation DEM Comparison

	10m NED			**10ft LiDAR**			**1m LiDAR**			**Ratio**	
	Terrace Elevation (m)	**Stream Elevation (m)**	**Height (m)**	**Terrace Elevation (m)**	**Stream Elevation (m)**	**Height (m)**	**Terrace Elevation (m)**	**Stream Elevation (m)**	**Height (m)**	**10m:1m**	**10ft:1m**
T1	168	162	6.0	173	162	11	173	162	11.2	0.5	0.9
T2	165	161	4.0	169	161	8	168	161	7.0	0.6	1.1
T3	165	162	3.0	165	162	3	165	162	2.5	1.2	1.2
T4	165	162	3.0	164	162	2	165	162	2.8	1.1	0.7
T5	162	160	2.0	164	160	4	164	160	4.3	0.5	0.9
T6	140	137	3.5	144	137	7	143	137	6.7	0.5	1.0
T7	137	134	3.0	138	134	4	138	134	3.7	0.8	0.9
T8	131	127	4.0	131	127	4	131	127	4.3	0.9	0.9
T9	128	122	6.5	126	122	5	126	122	4.6	1.4	1.0
T10	120	116	4.0	124	116	8	125	116	9.2	0.4	0.8
T11	120	111	9.0	120	111	9	120	111	8.5	1.1	1.0
T12	120	109	11.0	121	109	12	120	109	11.0	1.0	1.1
T13	110	107	3.0	110	107	3	110	107	3.0	1.0	1.0
T14	77	72	5.0	76	72	4	76	72	4.3	1.2	0.9
T15	69	65	4.0	70	65	5	70	65	5.2	0.8	1.0
									AVG	**0.86**	**0.97**
									STDEV	**0.29**	**0.11**

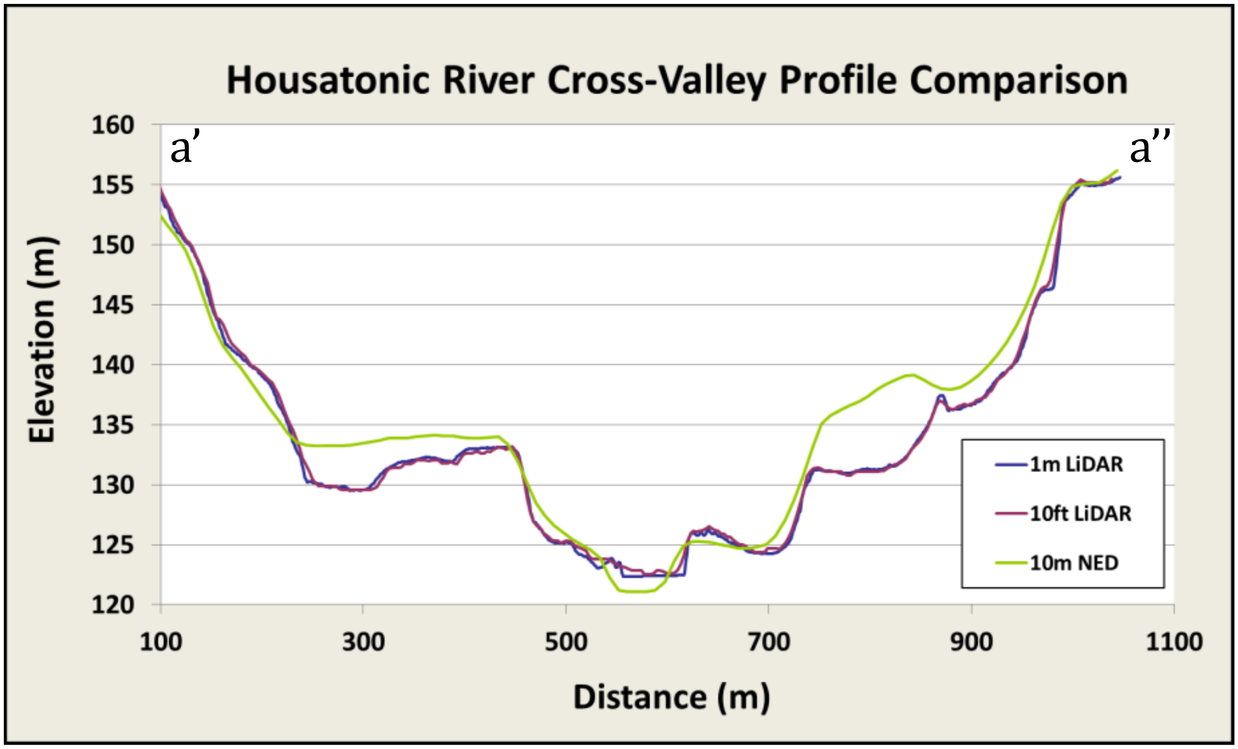


Figure 10. A comparison of three cross-valley profiles of the same location along the Housatonic River using different DEM elevations.

Digitally Mapping Terraces with TerEx

The primary analysis presented in this thesis relies on previously mapped terrace and fluvial deposits throughout Connecticut at 1:24,000 scale (Stone et al., 2005). To augment this mapping, an ArcGIS toolbox TerEx created by Stout and Belmont (2013) was utilized to assist in digitally mapping terrace and floodplain surfaces. This tool accommodates user-defined parameters (i.e. local-relief threshold chosen by a variable-size moving window, minimum area threshold, and maximum distance from the channel) to identify and map terrace and floodplain surfaces. TerEx also automatically measures planform area, absolute elevation, and height relative to the local river channel for each terrace. TerEx is utilized in this study across both main channels for the Housatonic and Farmington Rivers. The highest resolution DEMs were used, along with the digitized centerline from each river.

Step 1 of TerEx in ArcMap requires inputs of maximum terrace area, cell size, smoothing parameter, and focal window. Since the landscape in southern New England is complex as it is covered with glacial features and most rivers have mixed bedrock and alluvial valleys caused by a variety of factors, it is pertinent to run multiple trials for Step 1 (Table 2). After each trial is ran, it as analyzed and a new trial can be suggested from the last (i.e. an examination of which inputs are working, which need to be adjusted, etc.) This brute trial and error a step suggested by Stout and Belmont, allows for better understanding of precisely how the tool works for this study area,. After a trial was chosen as the most appropriate for mapping terraces, the chosen shapefile created in Step 1 is then edited to refine the file for Step 2. Editing consisted of removing areas that were evidently not a terrace surface. This ranges from surfaces that were small, flat areas on top of glacial features (i.e. tops of eskers or drumlins), obvious floodplains, roads, building foundations, etc. Other areas that appear to be terraces as first glance still needed to be gently modified. For example, some polygons appear as two different terrace surfaces, but are simply connected by a road or other very small flat surface, so these shapefiles are split accordingly. In some cases, terrace surfaces are neatly mapped by TerEx, however if the surface contains small changes in elevation via stonewalls, gullies, etc., the polygon will go around this blip in the flat region. These situations are solved by “filling in” the polygon to cover these small areas where it is evident that even if the surface is slightly modified, it is still part of the terrace. This issue occurs more in the higher resolution DEMs such as the 10ft and 1m LiDAR for Connecticut since these pick up on smaller details in the landscape.

After the shapefile is edited and saved to the users liking, Step 2 of TerEx can be run, which includes user-defined inputs including the new edited shapefile, the width of rivers mouth (simply determined by using the measure tool), and a designated reach length (500 m was chosen for all sites). Step 2 extracts data from the edited shapefile and forms a new shapefile called "terraces". This dataset contains information for the area of each terrace as well as absolute elevation, so deposits can then be labeled categorically by elevation. After TerEx was run for all parts of the two rivers (different parameters were needed for each change in DEM resolution), statistics were calculated, and the shapefiles were compared to previous terrace mapping from Stone et al. in 2005 with respect to the number of mapped terraces, location, size, elevations, etc.

Paleo-River Levels

Mapped terrace heights provide constraints on the paleo-river levels (ie., past longitudinal river profiles) for both rivers of interest. Initial paleo-river levels ($T_{0\alpha}$) were estimated using the terrace heights and broad calibrated ranges of radiocarbon dates from Stone et al. (2005). To determine paleo-river levels for a level for T_0 (the sediments and bedrock height before any incision immediately following deglaciation of the landscape), plotted terrace heights were used to draw an appropriate paleo-river level for a time immediately post-glaciation. The paleo-river levels do not follow one pattern downstream, as it is not expected there would be only one highest incision level due to deglaciation of the rivers. Levels were estimated for the highest elevation deposits, however some deposits seemed to be outliers, and a second, more suitable line was drawn at the level with a significant number of deposit heights ($T_{0\beta}$). The levels were then analyzed for patterns of incision, primarily looking for evidence of widespread incision or sediment damming and morphosequences.

DEM Sediment Volume Calculations

Mapped terraces and fluvial deposits preserve a record of the total amount of sediment that once filled the valleys of rivers studied. By utilizing DEMs and extracted terrace heights for both rivers of interest, it was possible to determine a conservative estimate for the total volume of sediment removed from the main stream channels. To accomplish this task, streams were divided into 5km reaches, and a separate DEM was clipped for each in the highest resolution available (i.e. 10m NED for Massachusetts, 10ft LiDAR for Connecticut, except for 1m LiDAR for northwest Connecticut). Five measurements of the highest terrace level in each reach were recorded and averaged (Table 3) as well as an average valley width for the reach. That average elevation was then be plugged into a raster calculator to digitally fill the valley for each reach. A cut fill tool operation was completed on the raster to extract a volume of the layer, giving the amount of sediment missing, or cut out from the main river valley by fluvial and glaciofluvial processes. The volumes from the reaches were summed to acquire a conservative estimate of sediment removed. Volumes for both the Farmington and Housatonic include both "with fill" (including net sediment accumulated downstream) and "without fill" (not including net sediment accumulated downstream) values.

RESULTS

Fieldwork: Trenching and Sediment Sampling

Fieldwork revealed that stream terraces contain variable sediments reflecting glacio-fluvial deposition associated with deglaciation and subsequent fluvial activity. For example, a trenched terrace adjacent to the Farmington River located at Brown's Harvest Farm in Windsor, Connecticut (Figure 4) shows a deposit is capped with 35 cm of coarse, well rounded gravel that overlays interbedded coarse and fine-grained sand as well as smaller amounts of silt (Figure 11). The deposits are well laminated and bedded, with some ripple marks clearly shown at two different depths (65 cm and 100 cm) (Figure 11), consistent with river delta sedimentation associated with Glacial Lake Hitchcock (16.5 -13.5 ka in age) capped by younger Farmington River gravels. We therefore interpret this site to be a <13.5 ka cut-fill terrace. Another trench and example of stream terrace deposits found along the Willimantic River (away from focus rivers Housatonic and Farmington but representative of terraces throughout Connecticut), revealed oxidized, weathered, coarse river gravel overlain by a thick organic rich soil. No dates are available, but the soil profile exposed in this pit is consistent with an old, late Pleistocene to early Holocene landform. We interpret this site to be a <18 ka cut-fill terrace associated with incision into the local, high glacial fill level after ice have retreated far upstream (Appendix II). Further details on grain size, grain shape, and Munsell color on sediment samples from select trenches as well as additional photographs can be found in Appendix II.

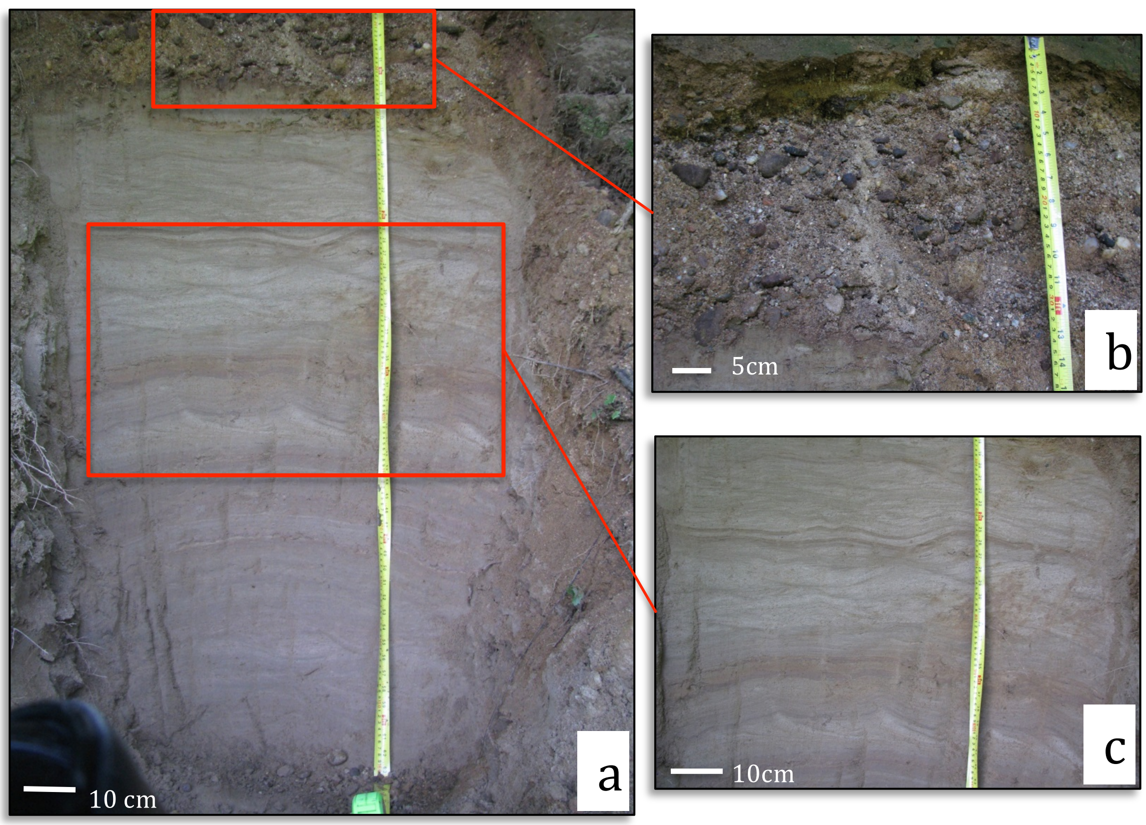


Figure 11. An example of a trenched pit, located in Windsor, Connecticut adjacent to the Farmington River.

Longitudinal Profiles and Terrace Heights

Longitudinal profile and terrace height analyses reveal river profiles marked by numerous knickpoints and over 300 instances of terrace trends resting well above modern floodplains of the Farmington and Housatonic Rivers. Figures 12a and 13a are initial longitudinal profiles produced by measuring elevations of the riverbeds, and Figures 12b, and 13b show the profile with adjacent river terrace elevations plotted. Deposits are colored similarly to the Quaternary map shapefile in GIS created by Stone et al. (2005). Dams along these profiles have been "removed", and an interpolated dashed line depicts a more true depiction of the rivers before anthropogenic alteration. This assists in interpreting paleo-river levels, as the dams are a modern component to these streams and we are focusing on the past 20,000 years. While deposits between the two rivers differ (i.e. specific deposits are tailored to each stream), maroon markers continuously represent mapped stream terraces (ranging in age from 16.5 ka to 7 ka) by Stone et al. (2005). Higher deposits depicted by various colors reflect a combination of kame terraces and variable fluvial/glacio-fluvial gravels mapped and associated with deglaciation (Stone et al., 2005) but with few constraints on absolute ages.

Deposit heights above the modern Farmington River range from 2 to 40 m (2-18 m for mapped stream terraces), and 3-45 m (3-20 m for mapped stream terraces) above the Housatonic. Three particular zones along these rivers were concentrated on, including the middle Farmington where the river flows southeast and northeast, the lower Farmington where the river flows east over the Holyoke basalt knickpoint, and the middle portion of the Housatonic in Connecticut (including the Falls Village knickpoint near the Connecticut-Massachusetts border to approximately 25 km downstream of the Bull's Bridge knickpoint). Terrace patterns in these three zones include; 1) more terrace levels found immediately down stream of knickpoints than upstream showing greater incision amounts, and 2) glacial and fluvial fill are consistent over the bedrock knickpoints.

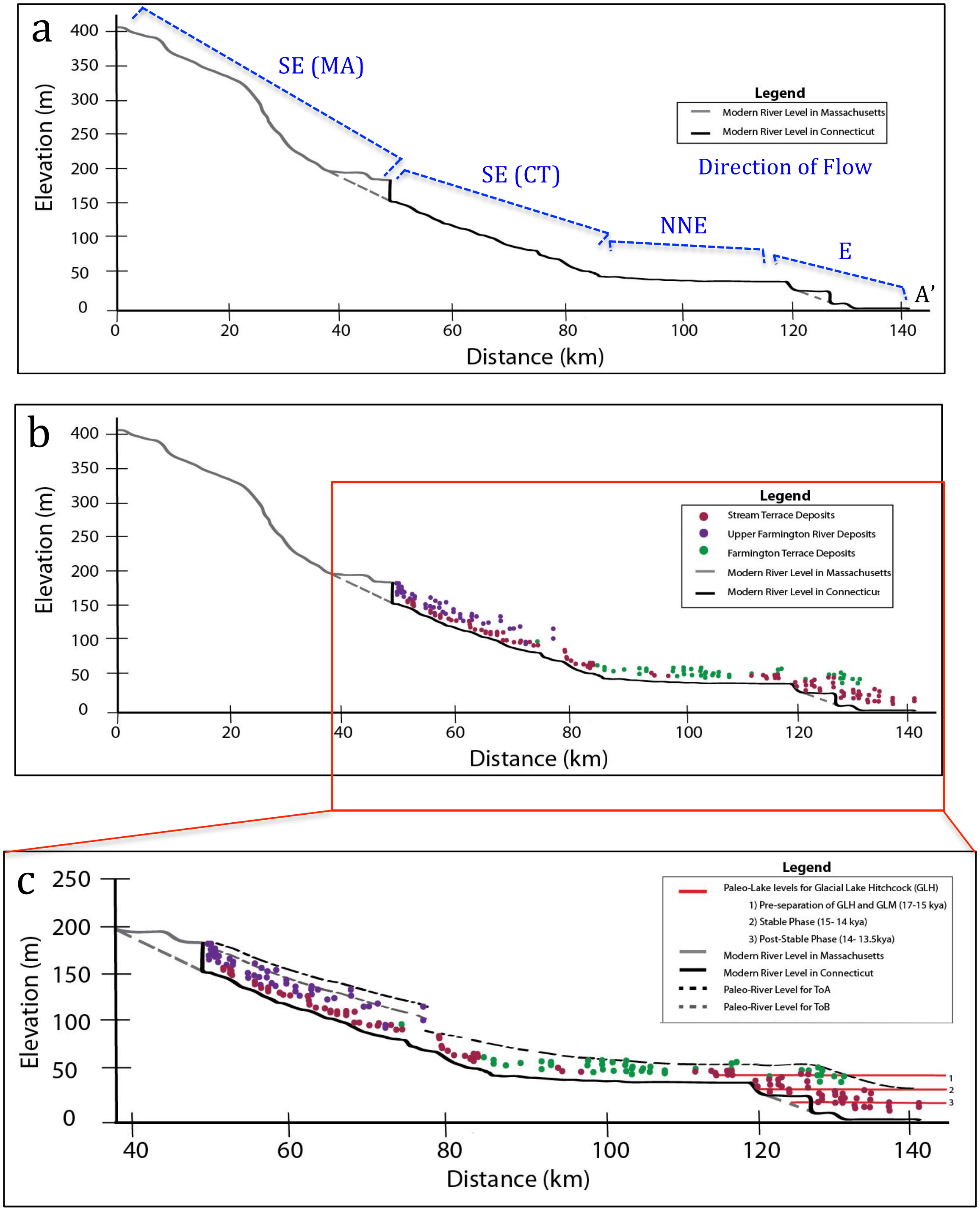


Figure 12. Longitudinal Profiles of the Farmington River showing a) the profile along with dashed lines under the profiles depicting interpretations of dams removed for a more natural river profile, b) the same profile with Quaternary deposits (Stone et al., 2005) of interest mapped above the profile (heights of these deposits were collected using GIS), and c) a close- up portion of the Farmington in Connecticut (indicated by the red box in 13b) showing interpretations for two paleo-river levels. The levels for Glacial Lake Hitchcock are also included for further interpretation.

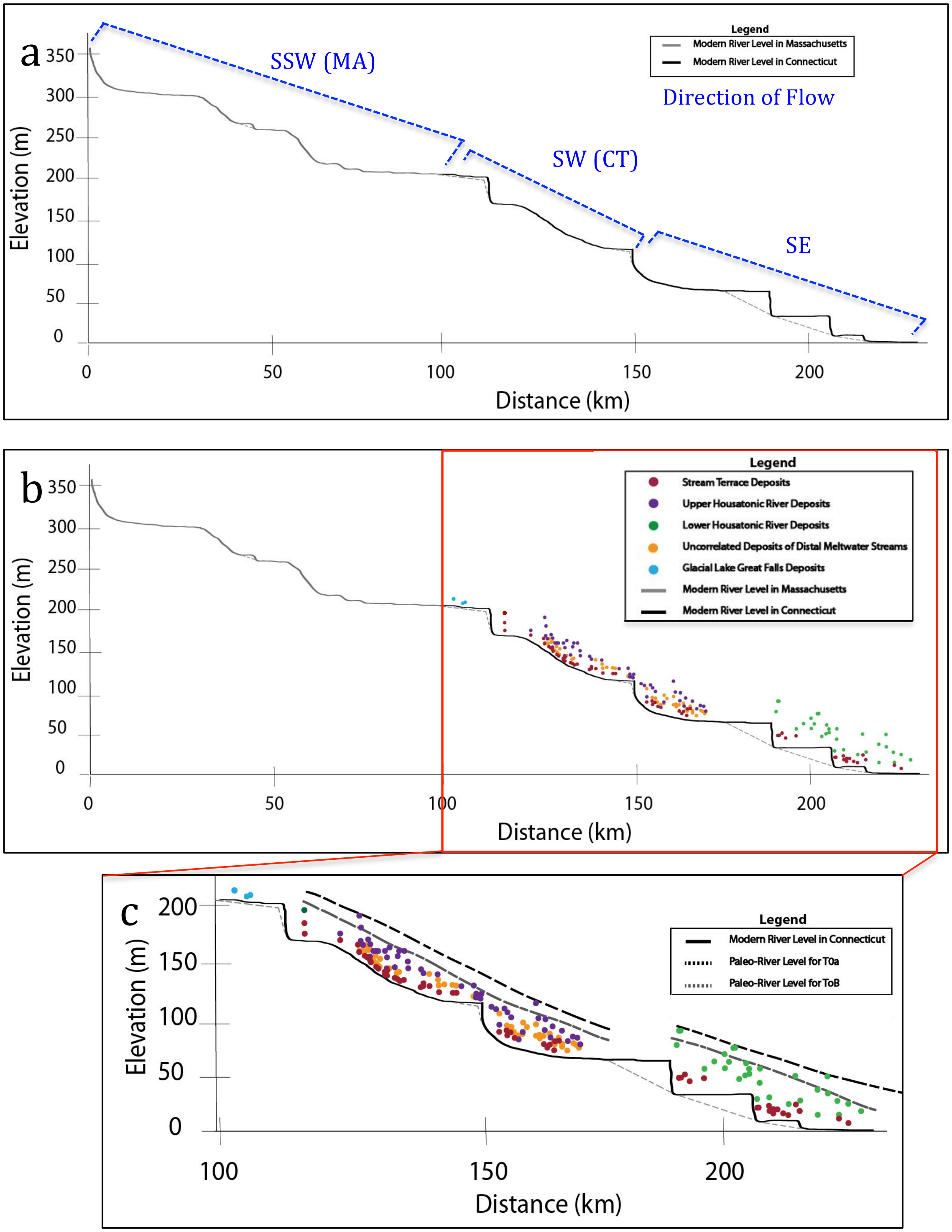


Figure 13. Longitudinal Profiles of the Housatonic River showing a) the profile alone with dashed lines under the profiles depicting interpretations of dams removed for a more natural river profile, b) the same profile with Quaternary deposits (Stone et al., 2005) of interest mapped above the profile (heights of these deposits were collected using GIS), and c) a close up portion of the Farmington in Connecticut (indicated by the red box in 14b) showing interpretations for two paleo-river levels.

Terrace Elevation DEM Comparison

A comparison of DEMs used in this thesis has allowed us to understand the amount of error when utilized multiple DEM resolutions from a variety of sources. Figure 10 shows three cross-valley profiles of the same location along the Housatonic River using different DEM elevations (i.e. 1m LiDAR, 10ft LiDAR, and 10m NED). Table 21is an analysis of 15 terraces adjacent to the Housatonic in northwest Connecticut, where all three DEM resolutions are available. This table shows the elevations of the river channel, elevations of the terraces, heights of the terraces above the river, and comparisons between the 1m LiDAR and 10ft LiDAR as well as the 1m LiDAR and 10m NED. Standard deviations range from 0.29 for 10m NED:1m LiDAR, and 0.11 for 10ft LiDAR:1m LiDAR. From this, there is difference of +/- 14 % between 10m NED and 1m LiDAR, and a +/- 3% difference between 10ft LiDAR and 1m LiDAR.

TerEx

The TerEx program, by Stout and Belmont (2013) was used in an attempt to digitally map terrace deposits and further our analysis along the portions of the rivers where terraces deposits are not currently mapped (i.e. Massachusetts). Figure 14 and Table 2 show comparisons of TerEx mapped stream terraces completed in this study to the previously mapped terraces by Stone et al., (2005). Many trials were run for both rivers, however the best examples are shown in both Figure 12a, which shows the closest mapping Stone et al. (2005) and TerEx were to each other, and Figure 12b where it is very evident TerEx does not include building foundations on the 10ft LiDAR near the Farmington River. Table 1 is a summary comparing numbers of terrace deposits mapped, average area, ad average elevation between previous mapping by Stone et al. (2005) and the terraces mapped by the TerEx program. Between 49 and 56 terrace deposits were mapped by Stone et al., (2005), while the TerEx program mapped 131-150 deposits. Average area of the deposits is subsequently higher ($0.41\ \text{km}^2 - 1.17\ \text{km}^2$) for Stone et al., (2005) than for TerEx (0.03 km^2- 0.42 km^2). Elevations of the deposits are more similar, ranging from 67-92 m for Stone at a., (2005) and 24-86 m for TerEx.

Table 2. TerEx and Stone et al., (2005) Mapping Comparison

River	**Stone et al., (2005)**			**TerEx (Stout and Belmont, 2013)**		
	Terrace Count	**Avg Area (km^2)**	**Avg Elevation (m)**	**Terrace Count**	**Avg Area (km^2)**	**Avg Elevation (m)**
Housatonic (CT)	49	0.41	92	150	0.03	86
Farmington (CT)	56	1.17	67	131	0.42	24

Total Post-Glacial Sediment Removal

To better understand amount of post-glacial river incision for the Farmington and Housatonic, the total amount of sediment removed from the main channels was calculated and can be seen in Table 3. The Farmington has had an amount of 22.2 km^3 (with fill) and 22.6 km^3 (without fill) removed, while the Housatonic has lost 50 km^3 (with fill) and 50.9 km^3 (without fill). We did not attempt to calculate incision rates with these volumes due to the unsteadiness of such incision and sediment transport due to a variety of geomorphic events over the last 20 ka. The values are also an absolute minimum, as it discounts tributary valleys.

Paleo-River Levels

Terrace heights can be used to determine paleo-river levels $T_{0\alpha}$ and $T_{0\beta}$ of the Housatonic and Farmington Rivers. These rivers levels likely persisted while glacial retreat was occur for these main stem rivers between ~19 and 17 ka (Ridge et al.; Figure 2). Figures 13c and 14c are the interpretations for paleo-river levels $T_{0\alpha}$ and $T_{0\beta}$ above the Housatonic and Farmington Rivers. Level $T_{0\alpha}$ is the initial paleo-river level, as it outlines the highest mapped deposits, while $T_{0\beta}$ represents a conservative high paleo-river level, as it does not follow the highest mapped deposits but rather the top of the majority of the deposits. Notice that paleo-river lines are not consistent downstream, as there are gaps in deposit heights, and more significantly, changes in the deposit types mapped. For example, the Housatonic River has Upper Housatonic River deposits adjacent to the upstream portions of the river in Connecticut, while to lower section is adjacent to Lower Housatonic River Deposits with a large amount of till between them. Since the Upper and lower Housatonic River deposits have different calibrated age groups, they can not be considered as one consistent paleo-river level for the entire river.

Relative ages from Stone et al. (2005) on Quaternary deposits utilized in interpretation specific to this study include Stream Terrace Deposits (16.5-7 kya), Glacial Lake Farmington Deposits (16.2-16 kya), Upper Farmington River deposits (16-15.8 kya), Farmington Terrace Deposits (13.8-13.4 kya), Lower Housatonic River Deposits (16.9-16.3 kya), and Upper Housatonic River Deposits (16.1-15.5 kya).

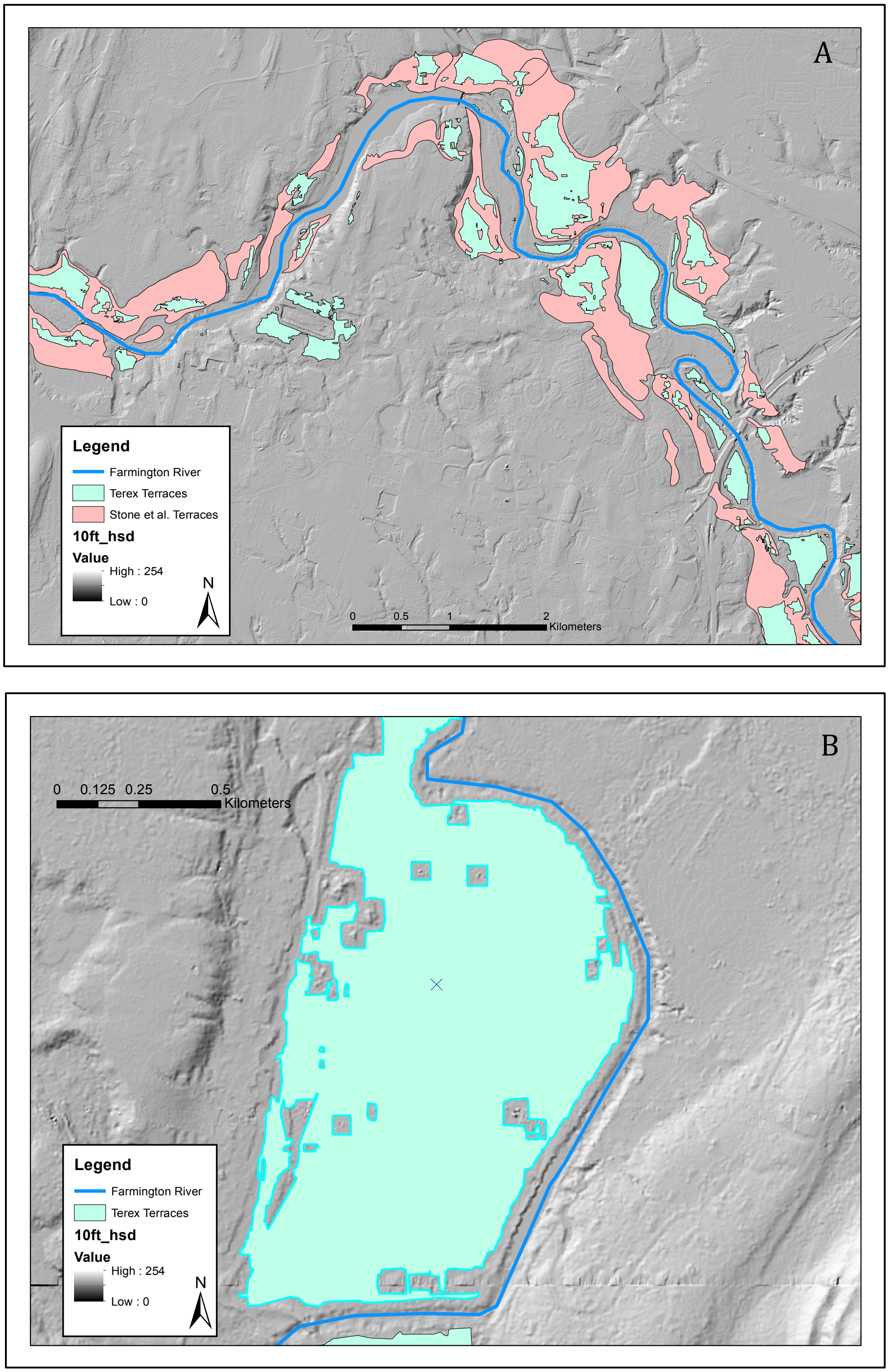


Figure 14. Two maps created in GIS showing a) comparison of Stone et al., (2005) and TerEx mapped terraces and b) an example of TerEx terraces mapping around building foundations.

Table 3. Calculation of Total Post-Glacial Sediment Removal

River	Volume (km^3)
Farmington Volume (with fill)	22.2
Farmington Volume (without fill)	22.7
Housatonic Volume (with fill)	50.0
Housatonic Volume (without fill)	50.9

DISCUSSION

Terrace Heights and Paleo-River Levels for the Farmington and Housatonic Rivers

Mapping Terrace Heights and TerEx

The extensive GIS and DEM analysis completed on these two rivers has allowed us to further understand the regional spatial variation of fluvial and glaciofluvial deposits, as well as interpret the behavior of the Farmington and Housatonic Rivers over the past 18-20 ka. Heights of all fluvial and glacio-fluvial deposits adjacent to the Farmington and Housatonic Rivers were examined. DEM comparisons allow us to constrain the error associated with various DEM sources, with high resolution being better (<3%) than lower resolution (10%). We can conclude the best represented and accurate study area is adjacent to the Housatonic River in northwestern Connecticut, as it was studied with the highest resolution DEM available.

Stone et al. (2005) mapped numerous terrace deposits throughout Connecticut in their Quaternary map, however Massachusetts has not been completed. Therefore, we used the TerEx program in an attempt to map more terraces digitally, allowing for additional analysis in the headwaters of these rivers. However, the results from the program did not add significant data to this study. When comparing the results, the TerEx program mapped many more terraces than Stone et al. (2005) (Table 2). Consequently, the average area of the TerEx terraces was also significantly smaller than those of Stone et al. (2005). This is due to the TerEx program breaking single terrace deposits into multiple pieces, as the program's main mapping method is to isolate terraces on the basis of subtle variations in elevation. For example, Stone et al. has mapped larger terrace deposits to represent different terrace levels, while the TerEx breaks them down into 2 to 4 smaller polygons. The difference in average elevation is less understood. TerEx terrace elevations are significantly lower than those of the Stone et al. terraces for the Farmington River. This could be due to the TerEx program measuring floodplain surfaces that were not removed before elevation analysis. An attempt was made to remove any floodplain surfaces before moving to step 2, however the program is set to map floodplains and it is possible that some were missed and included in the analysis.

Since the TerEx toolbox is semi-automated and relies on multiple user-defined parameters, there is also concern for user bias. For example, it is up to the user to decide the parameters for running Step 1, which decides how large of an area the deposits should be, how far in distance they should be from the river, and values the focal window and smoothing parameters. This can lead to error with digitally mapping these surfaces, however with significant knowledge of the study site, error can be lessened. The largest risk for user bias is during the editing of the shapefile, between steps 1 and 2. In an attempt to cut down on user error, editing was kept to a minimum and the TerEx tutorial created by Stout and Belmont (2013) was heavily utilized. Even though steps were taken to avoid as much error as possible, it is still easy to affect the number of terraces along with their area using the editing tool. TerEx was also particularly difficult to use on LiDAR, as the high resolutions led to a decrease in digital mapping capability (e.g., the "flat" terrace surfaces were too detailed and ridged for the program). For these reasons, TerEx deposit heights were not plotted above the profiles (Figures 13 and 14) or utilized in interpreting paleo-river levels. Although TerEx did not allow for extensive new mapping to be added to this study, it has potential to perform preliminary and detailed analyses on terrace location possibilities as well as terrace statistics (average height above the river, average area, etc.) when utilizing GIS for a large field area.

Terrace Height Analysis

Trends with deposits in relation to the current river profiles can be seen for both the Farmington and Housatonic. Some sections of the Housatonic River profile (Figure 13) show a "gap" in the terrace heights, which depicts an absence of easily mapped sand and gravel. This gap is mapped terraces is a break in deposition of meltwater fills. There are many levels of terraces immediately down stream of bedrock knickpoints, which is indicative of upstream migration or differential incision. Also, several locations along these rivers depict more of a widespread incision scenario (incision that is continuous for a large portion adjacent of the rivers), rather than concentrated portions of sediment (i.e. moraines and gravel deposits) discussed by Stone et al. (2005). It is possible that the few high terrace deposits in the upper Farmington River could be indicative of sediment dams that have been incised into, however a clear interpretation cannot be made as more data is necessary (e.g. radiocarbon dating and/or field observations). Therefore, these portions of the river were interpreted as widespread incision as this correlates to the majority of the terrace heights.

Cross sections reveal that the bulk of the cut-fill terraces previously mapped and then analyzed for this study are unpaired. This is consistent with river incision being relatively continuous throughout the last 18 ka with fewer period of long stability followed by events associated with rapid down cutting (which would lead to a more consistent paired level within the incised deposits). However, some of the highest kame terraces levels examined show more correlation to each other across stream, indicating paired behavior. This is consistent with the thought that the most intense and drastic event in these river valleys would have occurred immediately post-deglaciation in association with an increase in meltwater streams, lack of vegetation and maximum sediment availability and then rapid abandonment.

Paleo-River Levels

Interpreting previous river levels allows us to create incision patterns and scenarios for the Farmington and Housatonic Rivers. The complex glacial history of these rivers suggest a series of disjointed levels may apply for when portions of the rivers were still covered in ice, as well as different deposits being incised into over time. Also, the effect of isostatic adjustment needs to be considered, especially along the Farmington River as it flows in many directions (with each reach affected differently). The paleo-river levels presented here are preliminary, as dating of individual deposits has not been completed, however overall deposit age ranges from Stone et al. (2005) were used in interpolating these profiles.

Two different paleo-river levels were interpreted for the Connecticut portions of both rivers, and are labeled as $T_{0\alpha}$ and $T_{0\beta}$. Level $T_{0\alpha}$ represents the highest river level immediately post deglaciation and follows the highest deposits above the river, while $T_{0\beta}$ represents the second more conservative level for T_0 as it cuts out the highest mapped deposit levels, therefore eliminating any outliers in the data. Other profiles could be interpreted between these two levels, however without significant dates, we limit the number of interpolations.

Along the Farmington River (Figure 12), $T_{0\alpha}$ is significantly higher in the upper portions of Connecticut where it flows southeast, then in lower portions where the river flows northeast and cuts east into the valley. This is due to Glacial Lake Farmington located at the change in elevation for $T_{0\alpha}$, which would have slowed the process of incision. For the time that Glacial Lake Farmington existed (16.2-16 kya), it was the primary local baselevel for the upper portion of the Farmington River. Also, it is the only section to include the Upper Farmington River deposits, which have an approximate date of 16-15.8 kya (Stone et al., 2005). Here in the upper Farmington, we see evidence for widespread incision and argue that incision was driven by a change ratio between the sediment load and water discharge after ice retreated from the upper portion of the watershed. Once the sediment supply was cut off, the river cut into the glacial sediments. Level $T_{0\alpha}$ for the rest of the river downstream represents a shallow slope followed by a steeper decline as it outlines the elevation of the initial delta into the once existing Glacial Lake Hitchcock. This portion follows what are mapped as Farmington Terrace Deposits, which are dated at 13.8-13.4 kya (Stone et al., 2005), and depicts reworked fluvial and glacio-fluvial sediments.

The northeast flowing portion of the Farmington is also significant in searching for the effects of glacio-isostatic rebound. It is expected that higher terrace levels would be present in the downstream, northern portion of the north-flowing reach, as rebound amounts are more significant further north and away from the shore. However, there is no evidence along this reach to support the effects of that glacio-isostatic rebound. This suggests that this portion of the river has either (1) been modified so that the effects of rebound are not longer evident, or (2) Glacial Lake Farmington sediments altered the topography leaving a much more shallow change in terrace elevation for this stretch of the Farmington

The Housatonic River (Figure 13) has a different incision history than the Farmington, as it flows in a more southerly direction and into the Long Island Sound, leading to contrasts in both deglaciation and baselevel. Level $T_{0\alpha}$ along the Housatonic in Connecticut is broken into two segments; the upper portion of the paleo-level follows the path of the Upper Housatonic River Deposits, while the downstream $T_{0\alpha}$ level is higher above the river as it traces the highest levels of the Lower Housatonic River Deposits. The downstream portion of the Housatonic has been incising for a longer period of time, as the Lower Housatonic River Deposits were lain approximately 16.9-16.3 kya, while the Upper Housatonic River Deposits were lain around 16.1-15.5 kya (Stone et al., 2005). The more conservative $T_{0\beta}$ follows a similar path, breaking into two levels at the same reach of the river as $T_{0\alpha}$. This particular portion of the river is surrounded by glacial till and there are no preserved fluvial or glacio-fluvial deposits. The break in both $T_{0\alpha}$ and $T_{0\beta}$ also indicates a change in time. While the upper portion of the river (containing Upper Housatonic River Deposits) was still in the process of deglaciation, the lower portion of the river (containing Lower Housatonic River Deposits) may already have began incising. For both the Farmington and Housatonic, no attempt to create paleo-river levels in Massachusetts was made due to a lack of mapped Quaternary deposits to obtain terrace heights, as well as only lower resolution DEMs being available for the MA portion of these rivers. Once more complete data becomes available (e.g., more deposit dates, detailed mapping and high resolution DEMs), interpreted paleo-river levels should be reassessed and extended into Massachusetts.

Controls on Incision and Terrace Development in Southern New England

Lithology and Base Level Effects

This study shows substantial evidence that lithology regulates the pattern of incision, suppressing effects of regional base level changes. The Housatonic is a southward flowing river that was slowly deglaciated in a northerly direction and incised as sea level changed along with the climate, but there are many locations where bedrock emerged during incision and slowed upstream channel morphology (Figure 13). Along the Farmington River, the Holyoke basalt knickpoint emerged as it began to cut down into delta into Glacial Lake Hitchcock and has limited the amount of incision into the north-flowing portion of this river (Figure 12).

This is not to say that local and regional base levels are not important to these river systems. It is likely that the Farmington and Housatonic were affected by multiple smaller local base level controls within localized sections. Along the Housatonic, Glacial Lake Great Falls was also located just south of the Connecticut and Massachusetts border and would have led to a small, local baselevel for the stream north of the glacial lake. Sea level change and regional base level was never a major component for the Farmington River, but Glacial Lake Hitchcock would have strongly influence its lower half. The existence and slow drainage of this lake led to reworking of fluvial and glacio-fluvial deposits by the Farmington as it began to cut down into its previous delta.

Sediment Supply and Water Discharge

The interplay between of sediment flux and water discharge within a fluvial system has significant impacts on river incision. Immediately post deglaciation, southern New England was likely a transport-limited system as the glaciers dropped a thick coating of deposits over the underlying bedrock and sediment discharge was high. As the climate warmed, glacier retreated and the landscape slowly vegetated, sediment supply would have decreased while water discharge would have stayed relatively unchanged. This change in the ratio between sediment flux and water discharge would have lead to an initial pulse in river incision. The upper Farmington River shows this trend in the upstream portions. Here, far upstream from the effect of Glacial Lake Hitchcock and the Holyoke basalt knickpoint, there is little to no effect baselevel and river gradient changes, but rather the inevitability for the river to incise given a drastic change in the amount of sediment entering the system. The same cannot be said for the lower 25 km of the Farmington, where the drastic slope change generated by the existence and draining of Glacial Lake Hitchcock controlled incision and the pattern exhibited in the terraces.

Furthermore, since Glacial Lake Hitchcock drained much later that glaciers retreated in the upper portion (supported by the age of related deposits - Upper Farmington River deposits (16-15.8 kya) vs. Farmington Terrace Deposits (13.8-13.4 kya)) much later that glaciers retreated in the upper portion, the incision and development of the lower 25 km of the Farmington occurred long after changes in sediment flux have occurred in the watershed.

IMPLICATIONS

The Role of Bedrock Knickpoints

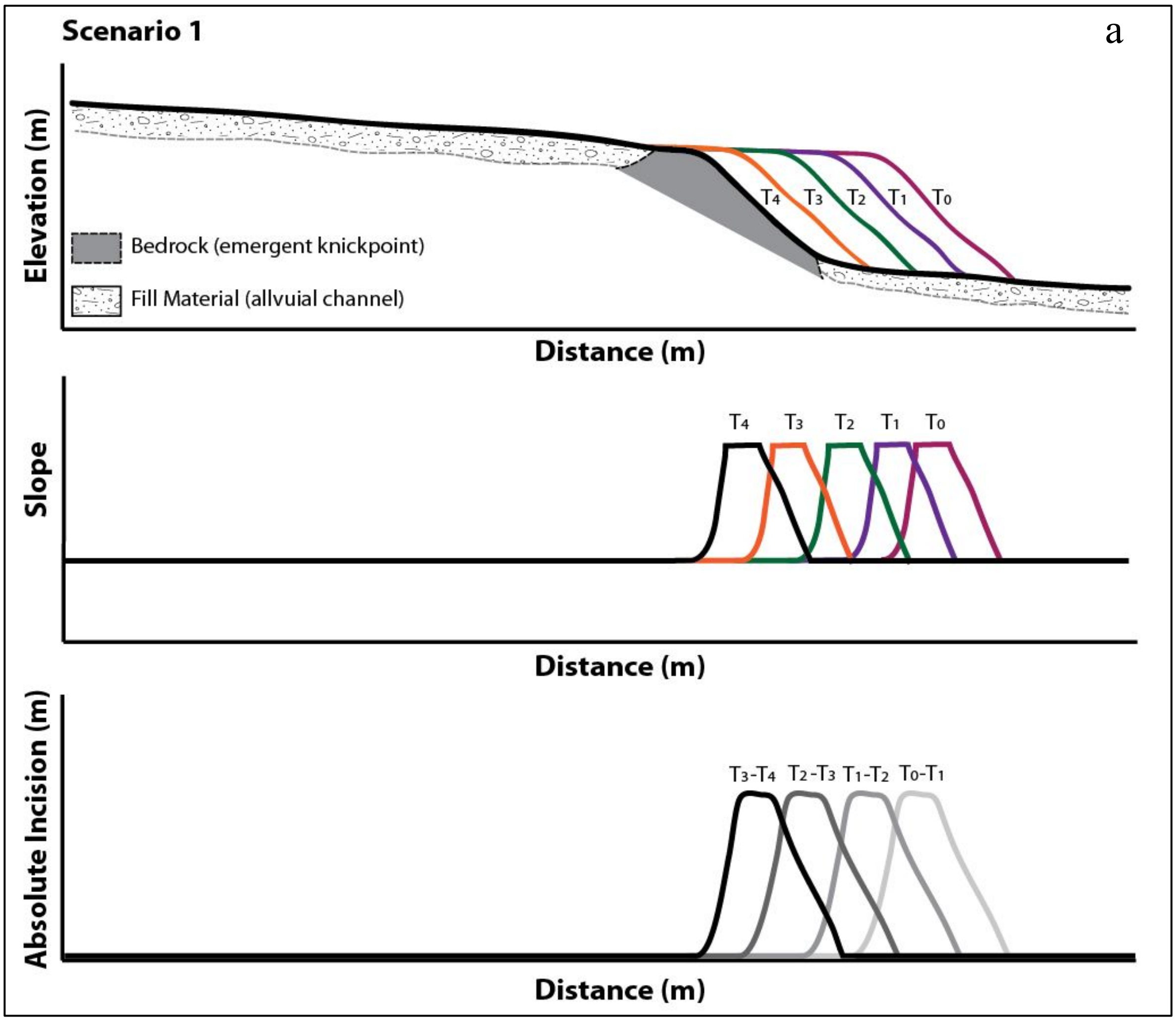
Knickpoint Observations

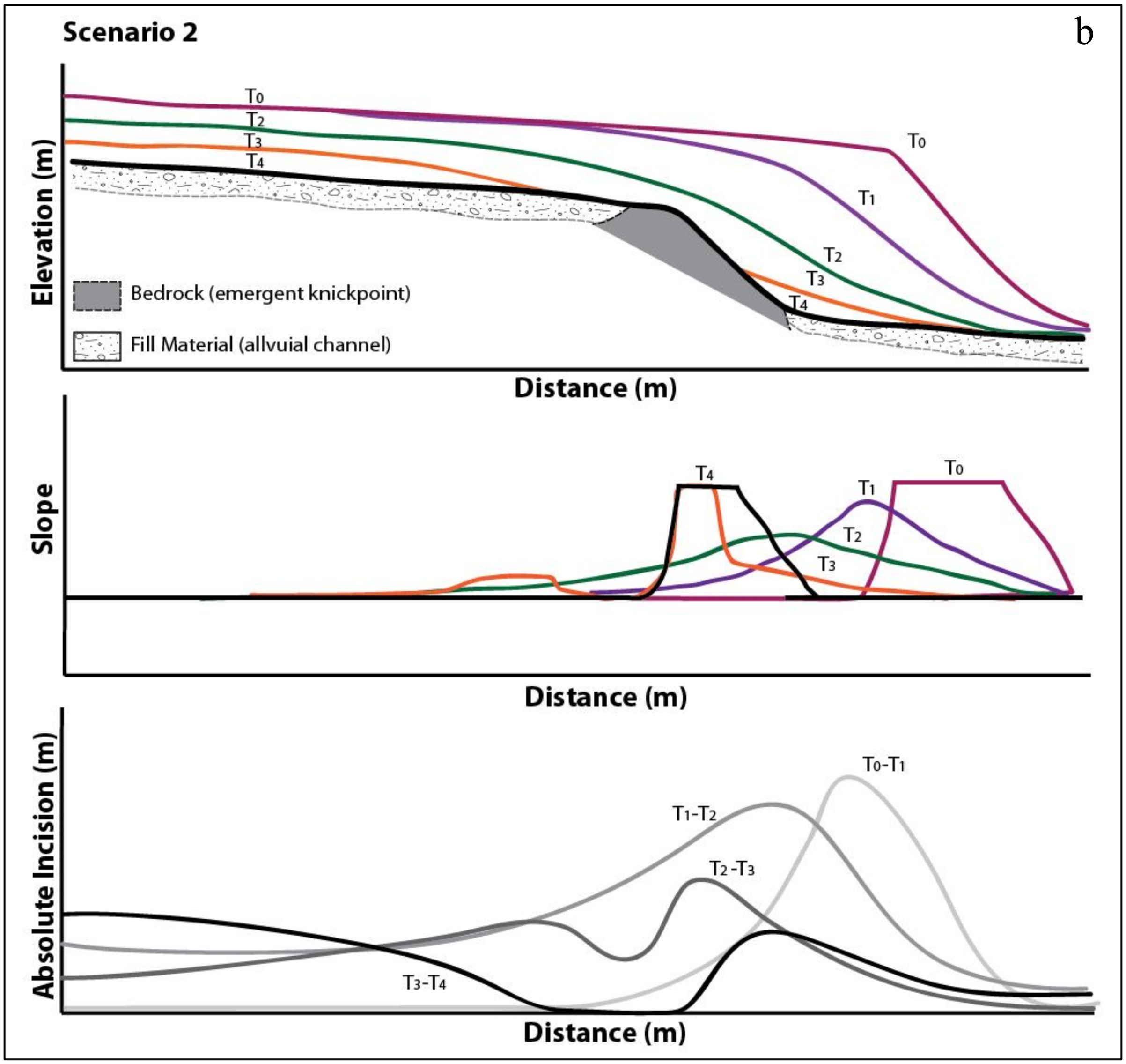
Many knickpoints found on these rivers are of different size, slope, and material, leading to different outcomes of river incision and channel profile shape. After deglaciation, as rivers incised in to glacial fill, these knickpoints emerged as either: (1) previous longitudinal profile knickpoint that were temporarily buried covered by the fluvial aggradation associated with high sediment flux; or (2) places where the post-glacial, incised path of the river became superimposed on bedrock ridges of previous river valley than were not part of the pre-glacial longitudinal profile of these rivers. Once exposed, knickpoints along both the Housatonic and Farmington rivers significantly affected the patterns of terraces and incision. New incision scenarios and conceptual knickpoint migration conceptual models are needed, rather than those that have been formerly discussed (Figure 4). New models need to allow for bedrock knickpoints to emerge during incision into unconsolidated glacial fill rather than simply migrate from downstream. With new models, the progression of terrace ages can be better tied to the migration and emergence of knickpoints. Once the impact of bedrock on incision is determined, it can pave the way to a strong prediction for terrace ages without detailed chronologies.

New Conceptual Models for Emergent and Migrating Knickpoints

The Farmington and Housatonic Rivers have unique incision patterns that do not fit current knickpoint migration models. Therefore, three new models have been proposed in this study, which explain detailed slope and incision patterns throughout the migration and emergence of bedrock knickpoints surrounded by easily incised, unconsolidated glacial fill. Figure 15 shows 3 scenarios of knickpoint migration and/or emergence that have been interpreted using Quaternary deposit heights and patterns of incision. Scenario 1 (Figure 15a) is an upstream migrating knickpoint with constant slope and no change in channel elevation upstream of the bedrock transitioning. This is similar to the previously discussed scenario shown in Figure 4, however in this case we argue that the knickpoint easily migrates through unconsolidated glacial fill and then resistant bedrock during significantly slows and prohibits further migration.   The slope remains constant in the knickpoint, and the pattern and amount of incision between the paleo-levels stays the same. Scenario 2 (Figure 15b) depicts a slope decline scenario where maximum incision takes place at the location of highest slope that slowly migrates upstream. Slope is lessened as the river cuts down, but when the bedrock emerges, the slope drastically increases while incision amounts decrease for the portion of the river over the knickpoint. Both the slope and incision patterns depicted here are complicated due to the emergence of the stronger material below. This scenario can be indicative of rapid base level fall (i.e. glacial lake drainage) with initial transported-limited (slope diffusion) behavior in easily incised glacial fill followed by detachment-limited behavior as resistant bedrock emerges. Scenario 3 (Figure 15c) is an emergent knickpoint model with widespread, constant slope incision and more incision downstream of the bedrock knickpoint once it emerges. In this particular scenario, slope and incision amounts remain constant, until the bedrock is uncovered.

At this point in the profile, slope dramatically increases only over the bedrock, and incision increases downstream of the knickpoint, as upstream incision stops due to the bedrock. All 3 of these scenarios can be utilized in any river system that has differential erosion patterns (i.e. mixed bedrock and alluvial channels).





Scenario 2
b
Elevation (m)
T0
T2
T3
T4
T0
T1
T2
T3
T4
Bedrock (emergent knickpoint)
Fill Material (allvuial channel)
Distance (m)
Slope
T4
T0
T1
T2
T3
Distance (m)
Absolute Incision (m)
T0-T1
T1-T2
T2-T3
T3-T4
Distance (m)

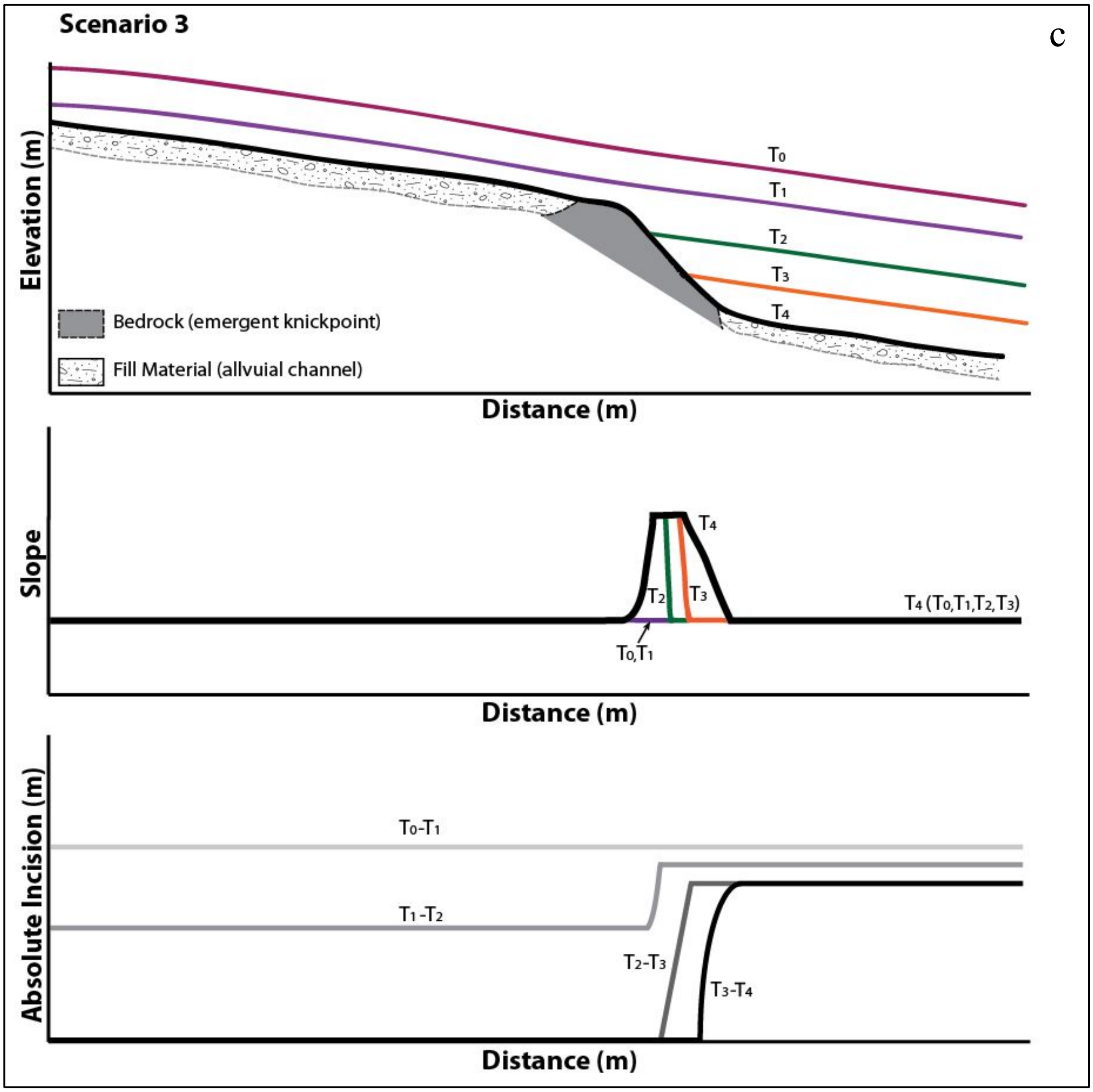


Figure 15. Three conceptual scenarios presented for knickpoint migration along with plots of absolute slope vs. distance and absolute incision vs. distance. Scenario 1 shows bedrock incision upstream with no change in incision or slope upstream of the knickpoint, scenario 2 is a model showing slope decline in a transport-limited system with an emergent knickpoint, and scenario 3 depicts constant slope and incision emerging a bedrock knickpoint.

Application of Conceptual Models

These models apply to multiple portions of the Housatonic and Farmington Rivers, and are a means to understand the intricacy of southern New England terrace distributions and inferred river incision (Figure 16). Scenario 1 cannot be seen in these rivers, as this model depicts constant slope, detachment-limited behavior and much of incision seen in these rivers is argued to be transport-limited in associated with a large quantity of unconsolidated glacial fill. However, scenario 1 could be used to describe the small amount of incision at the bedrock knickpoints themselves (i.e. the Holyoke basalt knickpoint along the Farmington, or Bull's Bridge and Falls Village knickpoints along the Housatonic). Scenario 2 is similar to the Holyoke basalt knickpoint, which is a mix of the bedrock overlain by glacial and deltaic deposits. After the ice receded and Glacial Lake Hitchcock filled in, the river began to incise and flow into the glacial lake laying down a large delta. As the lake drained, the Farmington incised lower to match baselevel and decline in slope as the river tries to reach its shallow, convex shape. The river eventually cleared enough glacial, deltaic, and glacio-fluvial material to expose the traprock ridge composed of resistant basalt bedrock, which immediately became a strong knickpoint that regulated channel slope and incision pattern. An example of scenario 3 can be seen in incision along the Housatonic at the Bull's Bridge knickpoint. Initially, there is an even slope with widespread incision for the region, and as the bedrock emerges, incision decreases upstream of the bedrock and continues downstream, reflected in the terrace pattern. In the field, the Bull's Bridge knickpoint displays the effects of increased stream power and active bedrock incision, evidenced by many potholes ranging from centimeters to meters wide. This would indicate that there is some bedrock incision along these profiles, however the amount is not as high as the incision of unconsolidated material. Scenario 3 is also consistent with the terrace pattern and constant slope incision observed in the upper Farmington River, however the knickpoints in this region are small relative to Bull's Bridge. Figures 16a depicts two potential examples of scenario 3 superimposed onto the Farmington and Housatonic Rivers and Figure 16b shows one potential example of scenario 2.

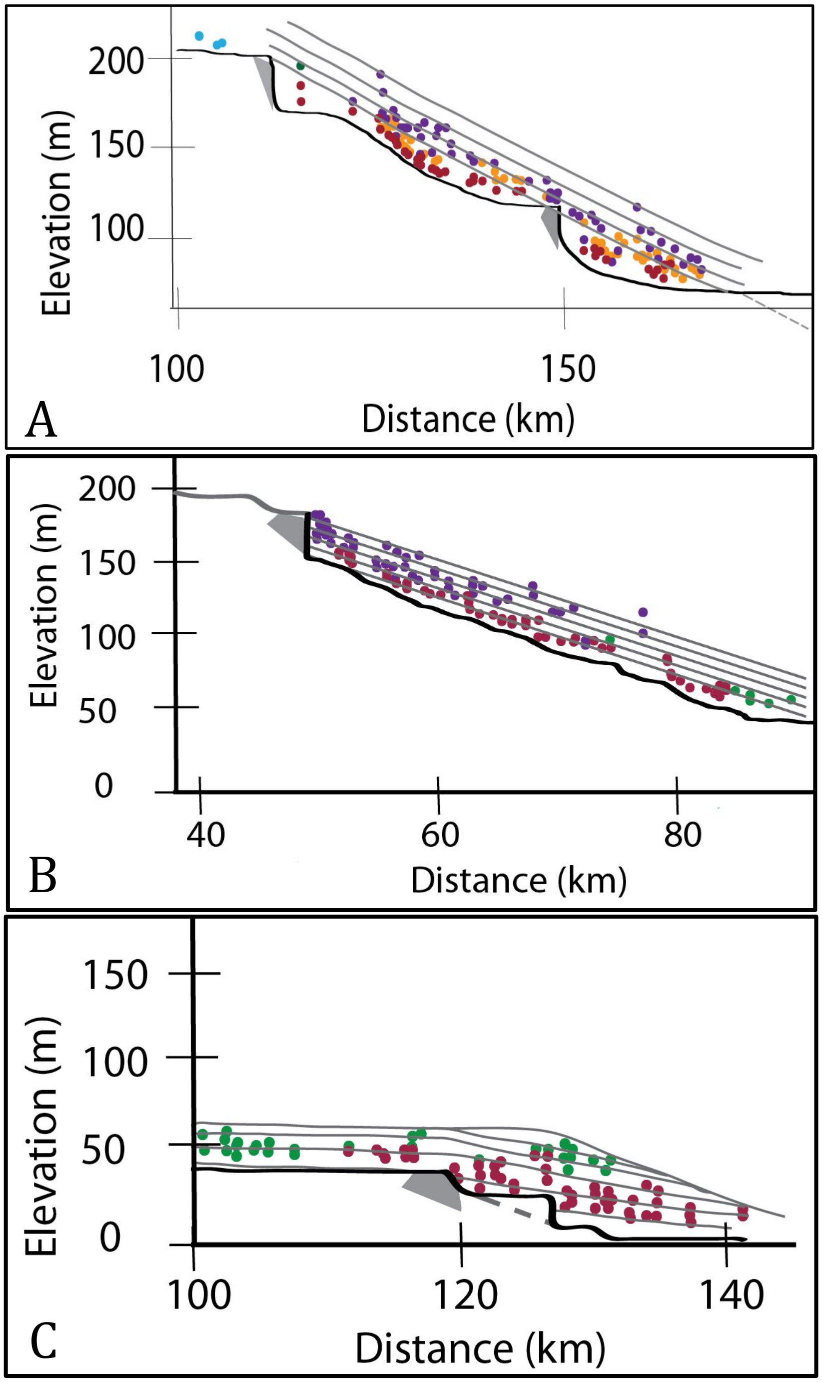


Figure 16. Paleo-river levels Ts shown interpreted for; a) downstream Farmington, b) upstream Farmington (in CT), and c) Housatonic River as a means to apply emergent knickpoint scenarios 2 and 3 to the study site.

It is important to note that interpretation of these knickpoint emergence scenarios in relationship to terrace deposits assumes that mapped units correlate in age. We observed many instances of terrace treads mapped by Stone et al. (2005) (i.e. stream terraces vs. Farmington and Housatonic Deposits) being assigned different units while their placement along longitudinal profile suggest that they are age correlative (see Figures 12 and 13). Unfortunately, since mapping was not completed for this study, we must rely on their previous mapping for the area. However, when comparing the patterns of incision with the differing mapped deposits, interpretations can be made that the mapping should be reassessed in some locations, and this would influence final application of the incision scenarios presented here.

Future Changes Along Southern New England Rivers

Anthropocene river incision has been linked to land use factors that alter basin hydrology, baselevel, sediment supply, and sediment transport dynamics (Mishra et al., 2007; Florsheim et al., 2013). For example, agriculture can lead increased sediment fluxes, urbanization can induce increased runoff, a dam can drastically alter the baselevel for the entire river upstream leading to sedimentation changes both upstream and downstream of the dam. As humans channelize with hard bank material, lateral erosion (a natural occurrence of rivers) is also prevented. This prevents widening that leads to narrower, higher stream power discharges capable of mobilizing sediment. These anthropogenic changes will need to be considered for understanding future slope and incision patterns on these rivers, and humans will only increase their alteration on river systems.

Climate change will also be a factor to increased magnitude and timing of river flow, as there is increasing potential for a higher frequency and magnitude of major storms in New England (in relation to global warming) (Florsheim, 2013). This increase in water discharge will lead to more rapid incision events and reorganization of fluvial and glacio-fluvial deposits, as well as change the course of river systems away from current steady state and towards a new equilibrium. This will lead to an increase in stream power, thus more incision into bedrock and causing more knickpoint migration.

CONCLUSION

Southern New England has a complex landscape history that includes 4 known glacial-interglacial cycles and the still-debated process, amount and timing of glacio-isostatic adjustment over multiple underlying bedrock types. This study proved successful at using GIS analysis and modeling, paired with fieldwork, to tell a story of post-glacial river incision and terrace formation for the Farmington and Housatonic Rivers. Using a combination of methods we show that the incision history of the Housatonic River was prominent when the ice still existed in Massachusetts and upper portions of Connecticut and became controlled by the Bull's Bridge and Falls Village knickpoints, while the Farmington River was primarily controlled by the Holyoke basalt knickpoint and local base-level; not only by Glacial Lake Hitchcock, but the lesser studied Glacial Lake Farmington as well. From this research, we can conclude the following:

1) A DEM comparison of the 10m NED and both 10ft and 1m LiDAR has shown that there is significantly less error for various forms of LiDAR, while the NED is less reliable in a study such as this where elevation values are key to analysis.

2) Interpreting terrace deposits has allowed us to understand paleo-river levels and incision amounts, and create knickpoint migration models.

3) After recreating past profiles for these two rivers longitudinally, it has become evident that bedrock knickpoints can emerge during incision and affect how rivers respond to a major event such as deglaciation.

4) Through profile analysis of these rivers and terrace deposits, the previous mapping from Stone et al., 2005 has some inconsistencies – places where stream terrace deposits and Housatonic and Farmington Deposits are mapped differently but appear to be part of the same paleo-river level when viewed along longitudinal profiles.

5) The TerEx program did not mapped terraces as planned due to the programs lack of flexibility on complex terrains (i.e. many paraglacial and periglacial landforms, as well as anthropogenic effects such as roads particularly visible in high resolution LiDAR data).

6) The effects of lithology and bedrock knickpoints hide any interpretable signal of base-level changes associated with differential glacio-isostatic adjustment in southern New England region.

7) The three knickpoint migration scenarios created here can assist in understanding the impact of bedrock on incision and lead to a robust prediction for terrace patterns and ages where dating is not possible.

8) It was expected that the influence of baselevel on terrace distribution and incision would differ significantly between these two rivers, however we see that local base levels (i.e. glacial lakes and knickpoints) are similar for both the Farmington and Housatonic.

In future studies, we hope to address more detailed effects on climate change in southern New England river incision processes such as what role has climate change (i.e. precipitation and river discharge changed) played on river incision throughout the late Pleistocene and Holocene. Also, a better understanding on the effects of glacio-isostatic rebound in New England could support further interpretations of timing and magnitude of incision. Additional fieldwork and collection organic material (i.e. wood fragments) would assist in better confining ages for these terrace levels, allowing for more precise interpretation of paleo-river levels. Intertwining future studies on regional baselevel changes would also assist in learning details of river incision as well as more thoughts on the effects of bedrock knickpoints.

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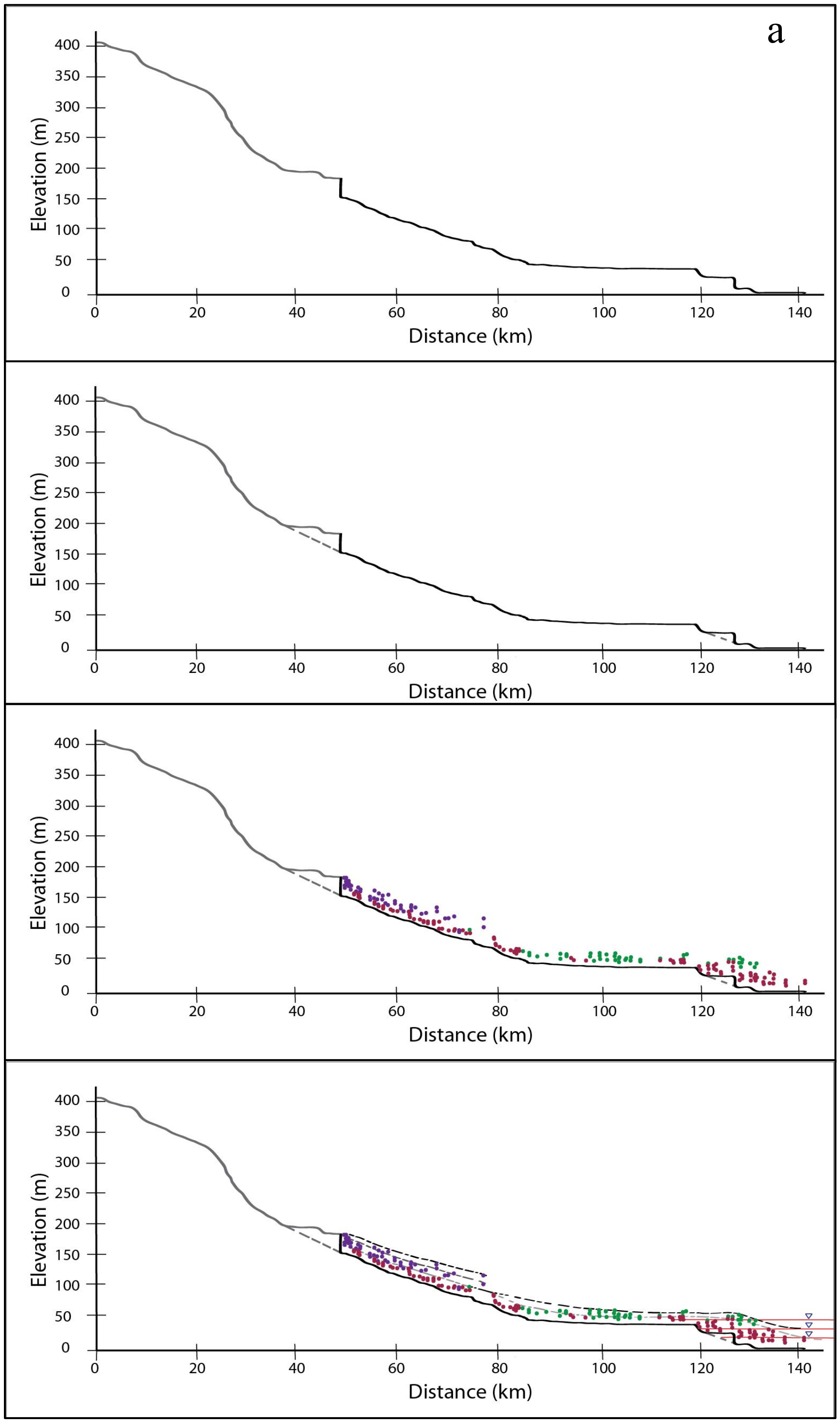
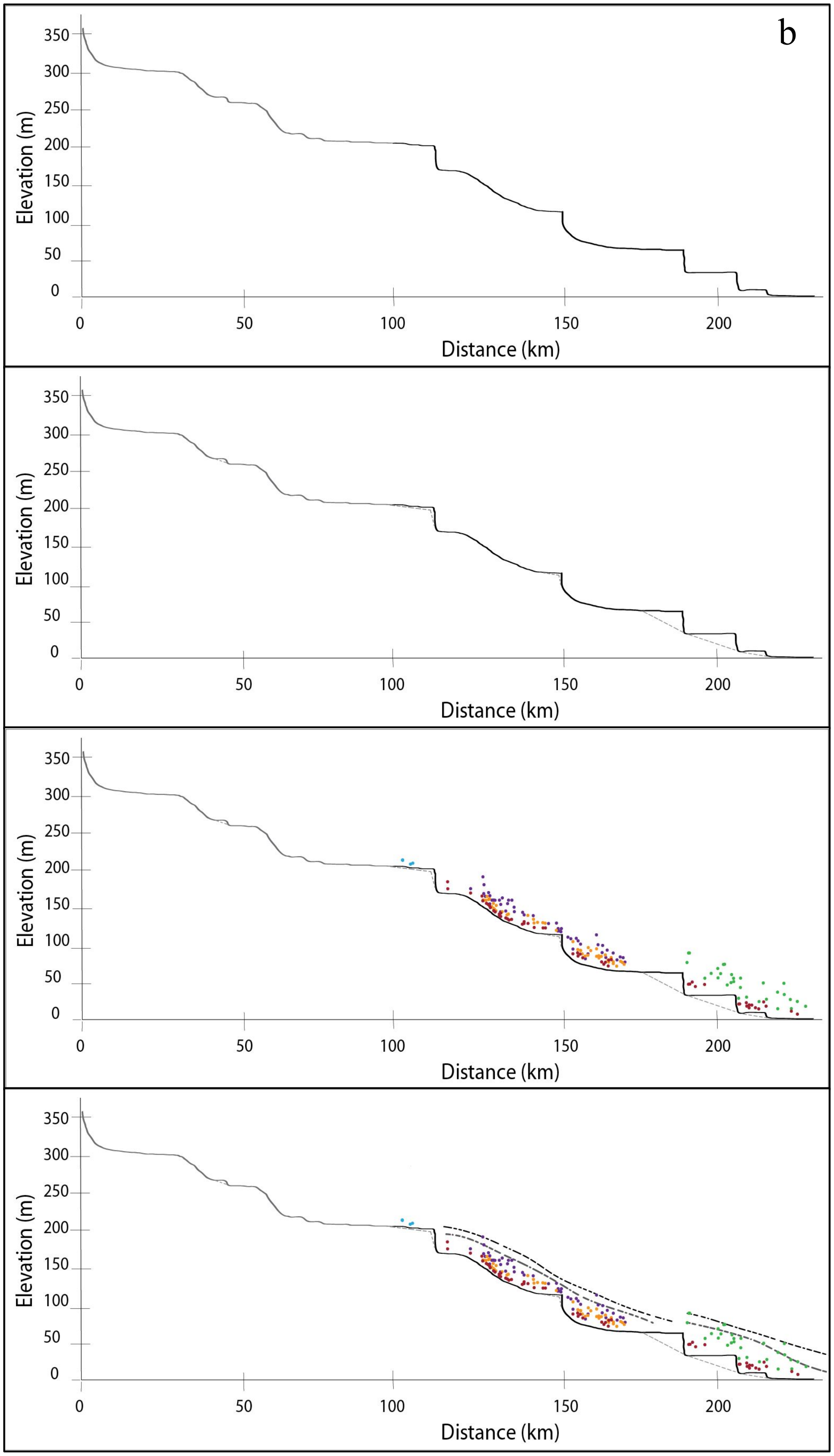
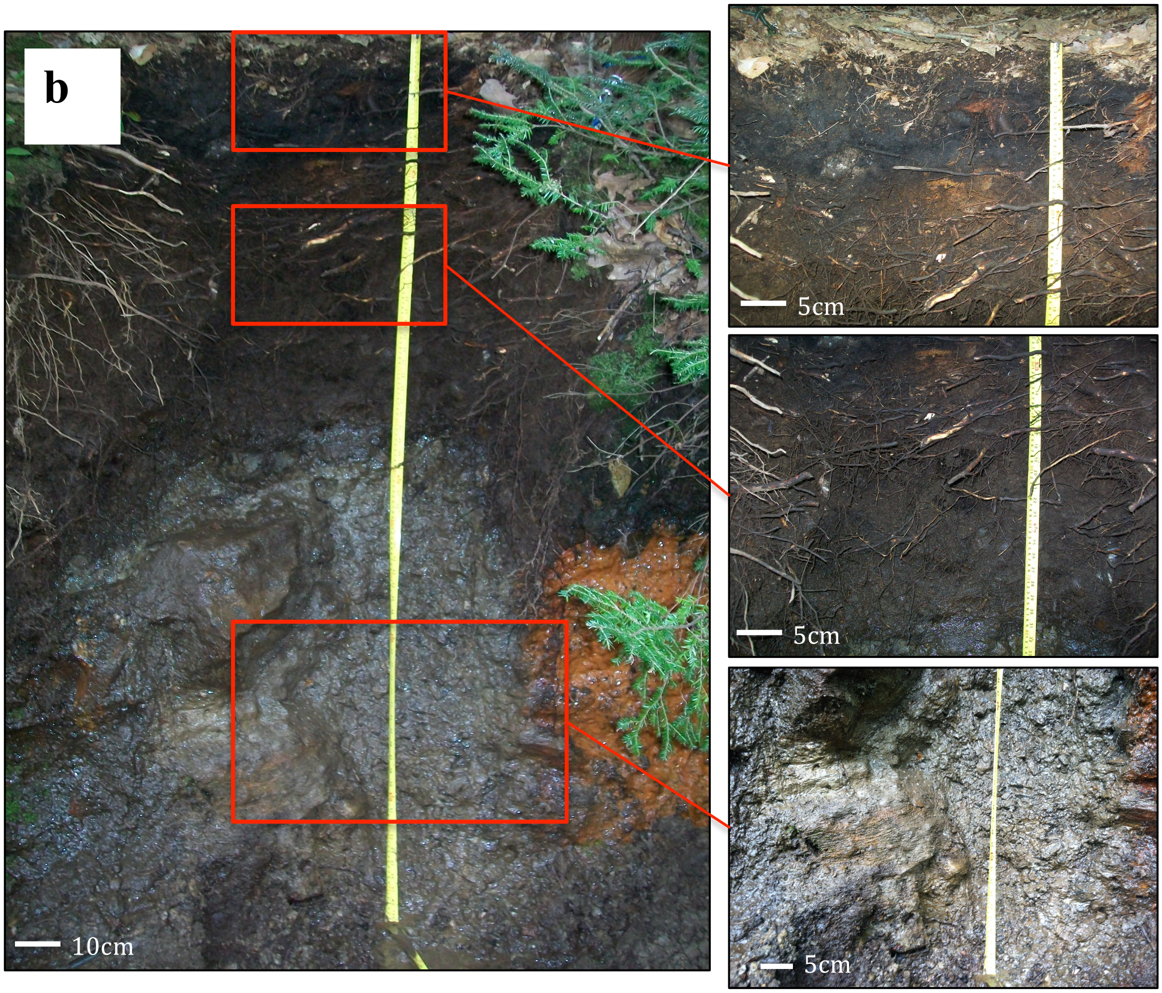
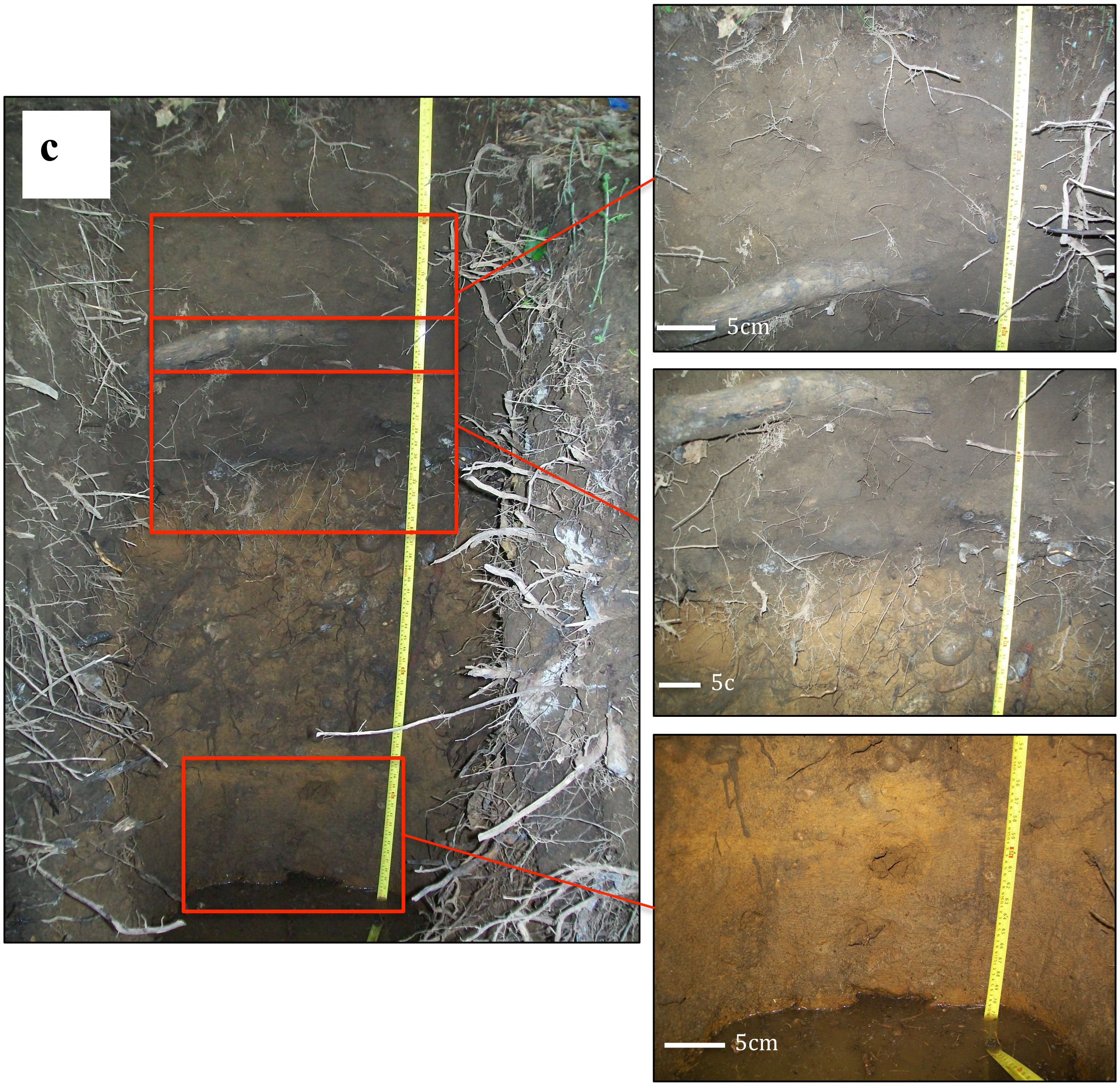
Appendix I. Steps taken to arrive at final, processed longitudinal profiles for the Farmington (Ia) and Housatonic (Ib) Rivers.




b
Elevation (m)
350
300
250
200
150
100
50
0
0
50
100
150
200
Distance (km)

Appendix II. Fieldwork Photographs from a) Farmington River at Brown's Harvest Farm in Windsor, Connecticut, b) Willimantic River near Brigham Tavern Road in Coventry, Connecticut, and c) Willimantic River on Spring Manor Farm in Mansfield, Connecticut.


b
10cm
5cm
5cm
5cm


c
5cm
5c
5cm

Appendix III. TerEx mapping trials and step 1 parameters for the Farmington and Housatonic River

Housatonic River							
Mass 10m NED							
Trial	**DEM**	**Change in Elevation (m)**	**Minimum Terrace Area (m)**	**Maximum Valley Width (m)**	**DEM Cell Size**	**Focal Window**	**Smoothing Parameter**
1	ma_10m_utm	0.5	500	1000	10	15	45
2	ma_10m_utm	0.25	250	1500	10	20	50
3	ma_10m_utm	0.5	250	2000	10	10	100
4	ma_10m_utm	0.3	500	2000	10	10	50
5	ma_10m_utm	1	500	2000	10	30	50
6	ma_10m_utm	5	500	2000	10	30	50
7	ma_10m_utm	3	500	2000	10	50	50
8	ma_10m_utm	4	500	2000	10	10	10
9	ma_10m_utm	5	800	2000	10	30	50
10	ma_10m_utm	5	500	2000	10	20	30
11	ma_10m_utm	1	500	2000	10	20	30
12	ma_10m_utm	2	500	2000	10	20	440
13	ma_10m_utm	10	800	2000	10	20	40
14	ma_10m_utm	5	800	2000	10	20	40
15	ma_10m_utm	8	750	2000	10	20	40
16	ma_10m_utm	10	500	1500	10	20	30
17	ma_10m_utm	20	500	2000	10	20	30
18	ma_10m_utm	20	750	2500	10	20	30
19	ma_10m_utm	10	750	2000	10	20	30
20	ma_10m_utm	10	1000	2500	10	20	30
CT 1m LiDAR							
Trial	**DEM**	**Change in Elevation (m)**	**Minimum Terrace Area (m)**	**Maximum Valley Width (m)**	**DEM Cell Size**	**Focal Window**	**Smoothing Parameter**
1	nw_1m	5	500	1500	1	5	45
CT 10ft LiDAR							
Trial	**DEM**	**Change in Elevation (ft)**	**Minimum Terrace Area (ft)**	**Maximum Valley Width (ft)**	**DEM Cell Size**	**Focal Window**	**Smoothing Parameter**
1	ct_lidar	5	1500	4500	10	20	30
2	ct_lidar	10	2000	5000	10	20	30
3	ct_lidar	10	2500	5000	10	20	40
4	ct_lidar	15	3000	5000	10	20	30
5	ct_lidar	15	3500	6000	10	20	30
6	ct_lidar	20	3500	6000	10	20	30

7	ct_lidar	20	3000	5500	10	20	30
8	ct_lidar	30	3000	5500	10	20	30
9	ct_lidar	15	3000	5500	10	20	40
10	ct_lidar	20	3000	5500	10	20	40
11	ct_lidar	10	2500	4500	10	20	20
12	ct_lidar	15	3000	3000	10	20	30
13	ct_lidar	10	3000	2000	10	20	30
14	ct_lidar	5	3000	2000	10	20	30
15	ct_lidar	10	4000	2000	10	20	30
Farmington River							
Mass 10m NED							
Trial	**DEM**	**Change in Elevation (m)**	**Minimum Terrace Area (m)**	**Maximum Valley Width (m)**	**DEM Cell Size**	**Focal Window**	**Smoothing Parameter**
1	ma_10m_utm	10	500	2000	10	20	40
2	ma_10m_utm	5	500	1500	10	20	30
3	ma_10m_utm	10	750	1200	10	20	30
4	ma_10m_utm	20	500	1500	10	20	30
5	ma_10m_utm	30	500	1800	10	20	30
6	ma_10m_utm	20	750	2000	10	20	30
7	ma_10m_utm	20	750	1500	10	20	30
8	ma_10m_utm	30	750	2000	10	20	30
9	ma_10m_utm	20	800	2000	10	20	30
10	ma_10m_utm	20	1000	2000	10	20	30
CT 10ft LiDAR							
Trial	**DEM**	**Change in Elevation (ft)**	**Minimum Terrace Area (ft)**	**Maximum Valley Width (ft)**	**DEM Cell Size**	**Focal Window**	**Smoothing Parameter**
1	ct_lidar	10	3000	2000	10	20	30
2	ct_lidar	10	2000	1500	10	20	30
3	ct_lidar	10	3000	1500	10	20	30
4	ct_lidar	20	2500	1000	10	20	30
5	ct_lidar	20	2000	1500	10	20	30
6	ct_lidar	30	2000	1500	10	20	30
7	ct_lidar	10	2500	1000	10	20	30
8	ct_lidar	10	2000	1200	10	20	40
9	ct_lidar	10	2500	1200	10	20	30
10	ct_lidar	10	2750	1200	10	20	30

Appendix IV. Table with area and elevations of terraces in Connecticut mapped by the TerEx program and Stone et al., (2005).

TEREX
Housatonic (Mass Only)

Area (m^2)	**Elevation (m)**
3531	1
18199	1
105480	2
124490	2
5243	2
4683	2
7323	2
19749	2
49526	2
9601	2
19071	3
200902	3
443142	3
270215	3
11269	3
5055	3
207408	3
49202	3
6596	3
245810	3
123774	3
2537	3
21555	3
4030	3
17821	3
110902	4
22177	4
32561	4
13498	4
30535	4
51481	4
37081	6
222299	6
208099	6
50224	6
42523	6
217127	6
14287	7
33888	7
242367	7
15069	7
96314	7
13479	8
9519	8
1563073	9
4385	9
34283	9
4793	9
1271301	9
1099258	10
730	10
2853	10
1356553	11
10678	11
12594	11
11183	12
17387	12
43999	12
11698	13
138973	14
16089	14
314	19
288	51

TEREX
Housatonic (CT 1m Only)

Area	**Elevation**
9087	2
41419	2
5748	2
206534	3
7305	3
75383	3
23600	4
454	4
975	4
24587	4
2902	4
5337	4
1065	4
10114	5
12956	5
18091	5
13872	6
9502	6
23579	7
55369	7
1406	8
48719	9
49504	9
45719	15
648	18
523	19
24064	22
447	24
132041	24
38424	24
62581	26
128356	40
904	43
915	65
11609	66
1045	66
1013	67
2582	67
1094	69
3625	69
8766	69
3289	69
8428	69
1291	70
151125	70
3641	70
1554	70
5825	70
13786	70
681	70
6677	71
28859	71
1366	71

12413	72
967	72
191145	73
4102	73
801	73
526	73
10488	73
426	74
456	74
5239	74
4151	75
1662	75
86588	75
4244	75
5027	75
5873	75
16539	75
6192	75
518	76
6250	77
5421	77
594	78
14497	78
15007	79
13304	79
471	80
40420	81
52259	81
1793	81
1383	81
3815	107
126386	111
37550	111
62608	112
83184	114
72151	115
26385	115
32724	116
8822	118
101559	118
55144	119
58046	120
267794	120
15705	120
4338	121
13385	121
723	121
2636	121
181224	121
581	122
1297	123
12043	124
14951	124
829	124
3447	124
32216	124
493	125
3393	125
12843	125
40395	125
2503	125
21075	125
77138	126
52237	126
8069	126
5754	127
16965	128
10262	128
67988	128
91621	129
162751	129
15586	131
147496	133
12499	134
68451	136
6658	136
11967	137
147215	139
5575	140
22120	141
3087	144
25642	145
15571	145
27134	145
10991	145
7130	146
3426	148
10635	149
11758	151
32799	152
17830	154
4153	154
13588	154
5540	155
12367	157
60060	158
65625	159
8349	161

TEREX
Housatonic (CT 10ft all)

Area	Elevation
201646	5
70235	5
199603	5
161858	6
76753	6
20544	6
325117	6
999815	7
62342	7
36743	7
216076	7
288049	7
6522	7
3739853	8
8614	8
26278	9
13088	9
84759	9
36503	9
64867	9
3996	9
86274	9
288705	9
75807	10
35351	10
2130247	10
337729	10
31153	10
177141	10
366955	11
16011	11
56462	11
92389	12
390881	12
1790500	12
51374	12

16335	12
72410	12
691311	13
232259	13
292507	13
294334	13
82247	13
1424549	13
337650	13
92472	14
227548	14
266949	14
14484	15
483065	15
81631	15
51493	15
27089	16
90258	16
31951	16
288949	17
20142	17
218929	17
185005	18
44939	18
105863	18
239721	18
12247	18
304463	18
95008	19
501057	19
30155	19
14226	20
89459	20
85727	20
10715	20
3049	21
186160	21
165542	22
92808	22
564111	22
52071	22
92823	22
7431	23
21037	23
254004	24
19738	24
14020	24
25971	25
25315	26
350531	26
21183	26
227530	27
135754	27
26729	27
888067	27
113052	27
37412	27
285711	27
46648	28
14516	29
66748	29
114320	32
869837	33
205312	34
197566	34
14708	36
111212	36
22346	36
62848	37
2618947	38
77409	40
112589	41
466163	44
75862	72
55154	79
33401	80

TEREX
Farmington (Mass Only)

Area	**Elevation**
130591	25
147468	25
142880	26
399514	30
67603	53
239022	53
89873	56
148053	58
222407	63
80799	69
81910	77

TEREX
Farmington (CT Only)

Area	**Elevation**
10519382	3
1555807	4
566647	4
2086179	5
3420	6
2783680	6
78415	6
222399	6
2925029	7
1674016	7
134584	7
427439	7
1802720	7
7255	8
14908024	8
14662	8
63632	8
271802	8
495	8
94241	9
21186627	9
147889	9
267360	9
948486	10
1287917	10
833928	10
356013	10
297204	10
8638775	11
1655898	11
463969	11
12213	11
142100	11
313978	11
452633	11
250513	12
104945	12
104771	12
72914	12
125052	12
355321	12
1027347	12
799540	12

16196	12
6843822	12
7136	13
269538	13
26977	13
47824	13
69528	13
27440	14
67858	15
60806	15
16913706	15
9059	15
984481	15
109540	15
69490	16
1032077	16
385131	17
32637	18
34209	18
131903	19
1526185	19
34567	19
165398	19
17406	19
121103	20
129676	20
158243	20
930992	20
875076	20
15605	21
7642	21
60318	21
487694	24
350123	25
2948232	25
551346	26
139906	26
72706	26
2492240	27
23714	28
5897031	29
2937473	30
219344	30
47220	30
689608	30
3259838	31
61725	31
648659	31
90071	32
23151	32
21361	33
29180	33
38363	34
194217	34
1512239	34
113774	35
189220	35
134341	35
7248	36
6912	37
28520364	37
30785	38
313702	38
18459	39
34946	39
99613	39
49591	40
8897	40
111100	41
52879	41
366663	42
179051	43
181198	43
2023189	44
414270	45
400764	45
4920636	49
6270567	51
43352	52
170004	52
33778	53
184349	55
602287	56
1020319	61
723437	62
45041	64
167752	71
108510	72
768964	85

STONE
Housatonic River

Area (m^2)	**Elevation (m)**
3043615	5
548616	27
1056981	28
2705929	30
1226358	36
1613881	38
2442420	45
3382252	47
421848	53
1329621	70
3876066	124
1286790	125
892147	127
794630	223
2248492	227
1411438	228
310504	253
244047	258
839362	259
1243003	265
123888	267
787382	268
1085738	271
487144	277
1717215	298
1070051	360
199936	364
2509427	366
2385807	371
2021431	374
364736	379
436226	388
1739866	394
610230	403
1152955	409
2745215	413
599379	414
5045077	422
515631	432
893029	452
707026	466
1070300	488

1423650	518
597260	531
850374	549
350314	551
603807	553
1083221	554
557910	554
3010405	561

STONE

Farmington River

Area (m^2)	**Elevation (m)**
11619892	51
2017686	55
10591925	56
4397669	66
886563	78
5963216	80
9158357	84
55023114	88
17476559	94
1308855	95
332423	101
1177183	101
638671	102
1003080	102
301974	105
831996	106
505229	107
186402	108
2345841	123
4485031	128
344504	135
1012451	135
786334	148
1911667	153
4216632	156
1390203	157
2485263	160
10338248	163
1498105	165
1072312	166
9253398	174
1671726	178
1041199	195
811582	202
3262844	205
5098727	220
2452987	220
1824609	251
1434426	301
3269747	313
3532862	313
4060491	314
655291	331
10946	355
1348957	357
297983	360
6795637	361
1045823	365
1187739	397
3335884	409
765304	423
2772971	442
1761168	454
1482679	476
959495	490
1773513	503
2203765	527